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ЗАПИСЬ ОБЪЕМНЫХ ПРОПУСКАЮЩИХ ГОЛОГРАММ СИНГУЛЯРНЫХ ПУЧКОВ В ФОТОРЕФРАКТИВНОМ КРИСТАЛЛЕ СИЛИКАТА ВИСМУТА

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Аннотация. Разработка и совершенствование методов получения и детектирования оптических вихрей позволяют расширить область их применения. В настоящей работе реализована импульсная запись динамических голограмм сингулярных пучков в фоторефрактивном кристалле силиката висмута. На представленной экспериментальной установке записывались пропускающие объемные динамические голограммы с использованием широкого спектрального диапазона для восстановления голографического изображения. В качестве источника сингулярного пучка применялась объемная статическая голограмма, записанная в слое фотополимера. Восстановление записанной

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голограммы осуществлялось с помощью непрерывного лазера с другой длиной волны, что позволило пространственно разделить записывающий и восстанавливающий пучки. Также был реализован интерференционный метод определения топологического заряда оптического вихря с использованием прошедшего и восстановленного лучей.

Ключевые слова: голография; фоторефрактивные кристаллы; оптические вихри; силикат висмута; интерференционная картина.

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RECORDING OF A VOLUME TRANSMITTING VORTEX HOLOGRAM IN A PHOTOREFRACTIVE CRYSTAL OF BISMUTH SILICATE

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Abstract. Recent breakthroughs in vortex beam research, characterised by structured beams bearing orbital angular momentum, have significantly transformed various applications of beams. These advancements have notably impacted fields such as advanced optical manipulation, high capacity optical communications, and super-resolution imaging. Undoubtedly, the development and refinement of generation and detection techniques for vortex beams play pivotal roles in enabling and enhancing their applications. In this work, pulsed recording of dynamic holograms of singular beams in photorefractive bismuth silicate crystals is realised. The experimental setup presented in this work is based on the recording of transmissive volume dynamic holograms, which allows us to use a wide spectral range to reconstruct the holographic image. A volumetric static hologram recorded in a photopolymer layer was used as a singular beam source. The restoration of the recorded hologram was realised using a continuous laser with a different wavelength, which allowed the recording and restoring beams to be spatially separated. An interference method for determining the topological charge of an optical vortex from the transmitted and restored beams was also realised.

Keywords: holography; photorefractive crystals; optical vortices; bismuth silicate; interference pattern.

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Introduction

Singular dynamic holography represents a novel advancement in the field of dynamic holography, particularly distinguished by its utilisation of light beams characterised by phase singularities, commonly referred to as optical vortices. A defining characteristic of these singular beams is the presence of specific points known as screw dislocations on the wave front. At these points, the light's intensity drops to zero, and the phase becomes undefined. An interesting phenomenon occurs when one traverses around a screw dislocation in the beam's cross section: the phase undergoes a change by an amount of $2\pi l$. Here, l denotes the topological charge, a crucial parameter in this context. Screw dislocations can be categorised based on the sign of l into positive (right-handed) or negative (left-handed) dislocations. One of the remarkable attributes of singular light beams is their ability to conserve their topological charge as they propagate. Despite the inevitable diffraction divergence, which affects the beam [1–4].

Photorefractive crystals, known for their nonlinear electro-optic properties, are highly effective for real-time capture of volume phase holograms [5]. These materials play a crucial role in the architecture of holographic storage solutions. Their unique capabilities make them ideal for a range of applications, including adaptive interferometry, associative memory systems, optical image enhancement, as well as data archiving and manipulation. The holographic recording process in these crystals relies on the spatial reallocation of charges under the influence of light rays, interacting with various impurity and defect centers that possess distinct properties [6; 7].

Singular optics and generation

Singular optics focuses on the exploration of wave field vortices and phase singularities, along with their inherent topological properties. These singularities, also known as optical vortices, are characterised by a zero intensity at their core, rendering the phase undefined. This phenomenon is often referred to as a «phase defect», where the light's phase exhibits a 2π spiral pattern around the beam's central axis during coherent transmission, a common occurrence in wave propagation [8].

The so-called vortex beam is a beam with a continuous spiral phase. In other words, the wavefront of the beam is neither flat nor spherical, but vortex-like with singularity. The vortex beam has a propagating property of cylindrical symmetry. In the center of this beam is observed a dark spot, exhibiting zero light intensity and maintaining this level of intensity throughout the propagation process. The phase wavefront of the vortex beam is distributed in a spiral shape, so the wave vector has an azimuth term, and it rotates around the vortex center. And precisely because of this rotation, the light wave carries orbital angular momentum.

In 1992, L. Allen and his colleagues [9] showed that a Laguerre – Gaussian beam can have a spiral phase structure, which has a significant orbital angular momentum per photon. In the center of this spiral phase there is a singularity, since the phase here is indeterminate, and the field amplitude also disappears so that a «black center beam» is formed at the center of the light wave. This revealed new understanding of the relationship between macroscopic optics and quantum effects. The complex amplitude of a singular light beam propagating along the axis z, can be written in the following form:

$$E(r, \theta) = A_0 \left(\frac{r}{r_0} \right)^{|l|} \exp\left(\frac{r^2}{r_0^2} + il\theta \right),$$

where $r = \sqrt{x^2 + y^2}$, x, y are Decart coordinates of a point in the cross section of a singular beam of radius r_0 (the center of the coordinate system is at the beam center); $\theta = \operatorname{arctg}\left(\frac{y}{x} \right)$ is an azimuthal angle; l is a topological charge. Computer modelling of the optical vortex propagation profile is shown in fig. 1, *b*.

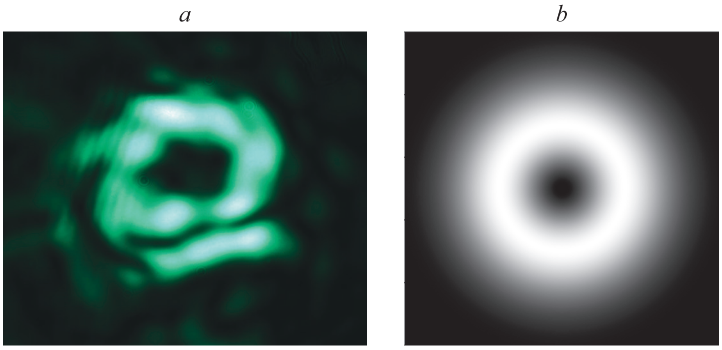

Fig. 1. Photo of the vortex beam (*a*)
and the result of numerical modelling of the singular beam profile (*b*)

Interference methods are widely used to determine the topological charge of an optical vortex. They involve the observation of special interference patterns when an optical vortex interferes with other waves. For example, when an optical vortex and a plane wave interfere, a characteristic fork is observed in the interference pattern (fig. 2, *a*). The light field intensity distribution of the interference pattern of an optical vortex and a plane wave can be described by the following formula:

$$I(x, y) \sim A_1^2 + A_2^2 \left(\frac{x^2 + y^2}{r_0^2} \right)^{|l|} + 2A_1A_2 \left(\frac{x^2 + y^2}{r_0^2} \right)^{\frac{|l|}{2}} \cos\left(\frac{2\pi x}{\Lambda} - l \operatorname{arctg}\left(\frac{y}{x} \right) \right).$$

Various methods can be used to produce optical vortices. One of them involves the use of in-cavity mold selection, where the Laguerre – Gaussian beam, a common example of a phase vortex beam, is generated in a cylindrically symmetric stable resonator. This is achieved by combining an associated Laguerre polynomial with a Gaussian distribution, and by fine-tuning the resonator's components, such as the cavity mirrors, to produce the desired Laguerre – Gaussian output.

Another innovative approach is the development of digital lasers, which represent a departure from conventional lasers that typically produce a single mode [10]. To access different modes in traditional setups, adjustments to the resonator's parameters are necessary. However, digital lasers, which have emerged in recent years, enable the generation of any desired laser mode, including vortex beams, without the need for structural modifications to the resonant cavity. This is accomplished through computer control, where varying electrical inputs dictate the laser's output, allowing for the creation of optical vortices.

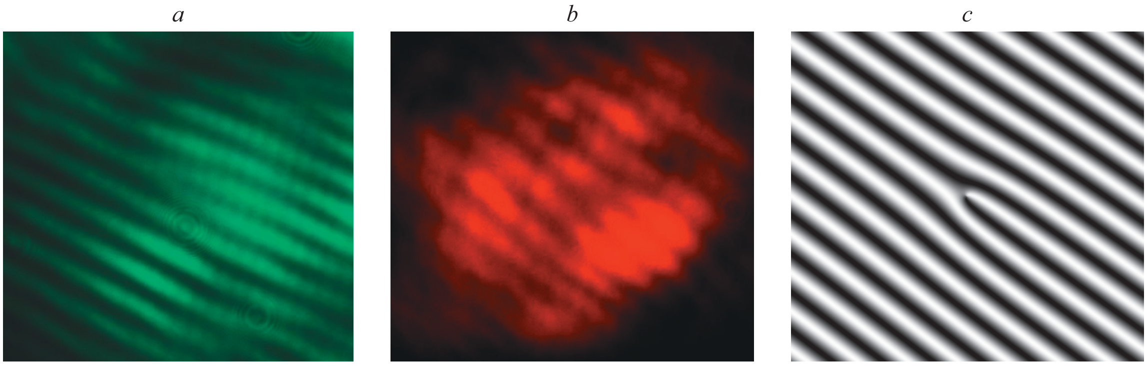

Fig. 2. Photography of the interference pattern of beams recording the hologram (*a*), beams restoring the hologram (*b*) and computer modelling (*c*)

Application a spiral phase plate (vortex lens) is an effective method for creating a vortex beam, characterised by its helical wavefront. This is achieved by transforming the wavefront of a standard Gaussian beam into a helical shape. By using a phase modulation device that imparts varying phase delays at different angular positions θ, the planar wavefront is reshaped into a helical form. A spiral phase plate, a type of optical element, facilitates this transformation [11].

Another approach involves the use of a fork-shaped grating (see fig. 2, *a*), a diffractive element with a specific fork-like profile. As a Gaussian beam pass this grating, in the diffraction pattern in the first order direction in the far field a vortex beam is formed. The topological charge of the vortex beam is determined by the number of grating splits. Due to their ease of fabrication and cost-effectiveness, fork-shaped gratings are widely used for vortex beam generation [12]. The simplest method of obtaining such a fork-shaped grating is to record a static hologram, which is formed as a result of interference of singular and plane waves. Such a hologram was used in the paper to obtain an optical vortex.

Photorefractive crystals

Photorefractive crystals are a class of nonlinear electro-optic materials known for its ability to dynamically record volume holograms. Their significance lies in their application within holographic storage solutions, playing a pivotal role in the development of advanced optical systems. These materials are integral to a wide are used in range of technologies including adaptive interferometry, associative memory systems, optical amplification, and the field of holographic recording and data management. The underlying mechanism of hologram formation within photorefractive crystals revolves around the spatial redistribution of electric charges under the influence of the light field in the interference pattern. This redistribution occurs between different parts of the crystal, as a result of which they acquire different optical properties under the action of the light field. Notable examples of photorefractive materials include lithium niobate ($LiNbO_3$), barium titanate ($BaTiO_3$), bismuth silicon oxide (BSO), and bismuth germanium oxide (BGO) [13].

The focus of this study is recording holograms of singular beams in sillenite-type photorefractive crystals. Sillenites have garnered significant attention in the photorefractive domain due to their exceptional sensitivity and minimal energy requirements for pulse recording $\sim$1–10 $mJ \cdot cm^{-2}$ [14; 15]. In sillenite crystals, the photorefractive effect arises from the activity of both electrons and holes, contributing to the demonstration of two types of photoconductivity. Although electron-driven conductivity predominates, the presence of hole migration tempers the resultant space charge field from the electron grating, leading to a dynamic equilibrium between the two types of charge carriers.

Experimental setup and results

To study the processes of recording dynamic holograms in photorefractive crystals, an experimental setup was assembled, the scheme of which is shown in the fig. 3. The second harmonic of pulsed Nd : YAG laser *1* with wavelength $\lambda = 532$ nm and a pulse duration of 20 ns was used as a recording source. Then the laser radiation is divided into two identical beams by a semi-transparent mirror *8*. A plate *9* with an already recorded hologram of a singular beam in photopolymer was placed on the path of one of the beams. Mirror *3* directed the reconstructed singular beam to the crystal as a signal beam. Another beam from semi-transmitting mirror *8* was also directed to the crystal by mirror *4* as a reference wave. As a result of interference of these beams in the crystal a hologram was formed.

The resulting hologram was reconstructed using a continuous helium-neon laser *11*. To determine the topological charge, both the transmitted and diffracted beams of this laser were used in the interference scheme.

This scheme includes mirrors *6* and *7* as well as a dividing cube *13*. To equalise the intensities of the waves involved in the interference, a neutral light filter *12* was installed on the path of the passed wave. The obtained interference pattern was recorded using camera *14*.

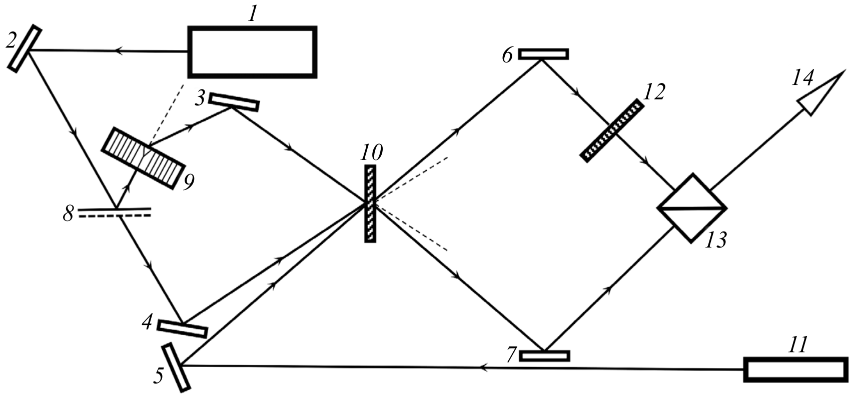

Fig. 3. Scheme of the experimental setup for recording dynamic hologram of singular beam in bismuth silicate crystal:
1 – Nd : YAG laser (second harmonic, 532 nm);
2, *3*, *4*, *5*, *6*, *7* – mirrors; *8* – semi-transmitting mirror;
9 – vortex grating ($l = 1$); *10* – BSO crystal; *11* – helium-neon laser (632.8 nm);
12 – neutral optical filter; *13* – divide cube; *14* – CD camera

Figure 1 shows images of the singular beam, which was used as a signal wave for recording the pulse hologram and the result of numerical modelling of the singular beam profile. As can be seen from the figure, the obtained beam has a «doughnut-like» of the spatial intensity distribution with a minimum in the center, which is characteristic of an optical vortex.

The interference of an optical vortex and a plane wave in a bismuth silicate crystal resulted in the recording of the interference pattern shown in fig. 2, *a*, with a characteristic «fork». The obtained hologram can be reconstructed by helium-neon laser radiation by selecting the correct angle of incidence of radiation according to the Bragg condition. As a result of diffraction, we form a diffracted beam, which is an optical vortex. Further, the classical interference scheme of topological charge determination is used by determining the number of splits (additional lines) and the direction of the «fork». Figure 2, *b*, shows the interference pattern of the past and diffracted beam of the helium-neon laser. As you can see, the number of splits and their direction coincides with the topological charge of the fork-like diffraction structure used to record the grating in the crystal.

Conclusions

To record and recover singular dynamic holograms in photorefractive bismuth silicate crystals, we have developed an experimental scheme involving the use of a pulsed laser for record hologram and continuous laser light for its reconstruction. A static hologram, which is a fork-like diffraction grating was used as the source of the optical vortex. When light passes through it, an optical vortex propagates in the direction of the first order of diffraction. After reconstruction of the obtained dynamic hologram of the singular beam, two beams (the passed and the reconstructed beams) were observed at the crystal exit. These beams were brought together and an interference pattern with a characteristic fork was recorded on the CD camera. A distinctive feature of this scheme is the use of the passed beam as a plane wave source for the interference analyses of the topological charge of the optical vortex. As many photorefractive crystals have optical activity, the use of two passing beams can compensate the effect of optical activity and obtain a high quality interference pattern with a high visibility value.

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