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Detection of orbital angular momentum of light by forked diffraction method

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Abstract. Orbital angular momentum (OAM) is a characteristic of wave describing its spiral phase front. These waves can be applied in various fields such as quantum communications and computations, hence, there is a need for a compact and simple method of its generation and detection. Here we describe an experimental realization of OAM light beams via the forked diffraction method.

Keywords: orbital angular momentum (OAM), vortex light, detection, computer-generated holographic gratings, topological charge

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Детектирование орбитального углового момента света методом вилочной дифракции

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Аннотация. Орбитальный угловой момент (ОУМ) – характеристика волны, описывающая ее спиральный фазовый фронт. Волны с этой характеристикой могут быть применены в различных областях – таких, как квантовые коммуникации и вычисления. Отсюда возникает необходимость в простом и компактном способе генерации и детектирования волн с ОУМ. В данной работе описывается экспериментальная реализация ОУМ световых пучков методом вилочной дифракции.

Ключевые слова: угловой момент (ОУМ), закрученный свет, детектирование, голографические решетки, топологический заряд.

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Introduction

Quantum communications is a novel technology in the field of information transmission which enables ultimate signal protection from eavesdropping. In the simplest version, quantum information is encoded in a two-dimensional degree of freedom, e.g., polarization of light. The use of higher-dimensional degrees of freedom significantly improves quantum communication protocols, for example, providing longer secure communication distance [1-4]. Orbital angular momentum (OAM) of light is a degree of freedom which can be used for multidimensional quantum information encoding. Currently, there are several methods for generation and detection of OAM. Here we consider the forked diffraction method which is remarkably flexible and simple in use and allows for both generation and detection of OAM with the same equipment. The method employs special holographic masks which we produce by lithography.

Theoretical

The local wave vector of a plane wave Gaussian beam is parallel to the direction of beam propagation (Fig. 1,*a*). In contrast (Fig. 1,*b*), beams that carry OAM have a non-zero tangential component of the local wave vector, so the wave has a spiral phase front [5-8]. The number of revolutions around the center of the beam is a topological property which does not depend on the local perturbations, hence OAM is described by the topological charge L. The magnitude corresponds to the number of revolutions, and the sign reflects the direction (negative L stands for clockwise and positive L for counterclockwise rotation) [5]. The maximum modulus of the topological charge determines dimensionality of the OAM degree of freedom which can be used to transmit information in high-dimensional quantum communications.

Many methods of generation and detection have been already described in literature. The method of forked holographic gratings, which we have chosen for our experiment, employs special holographic masks (Fig. 1,*c*). Each holographic pattern is generated by a special program and

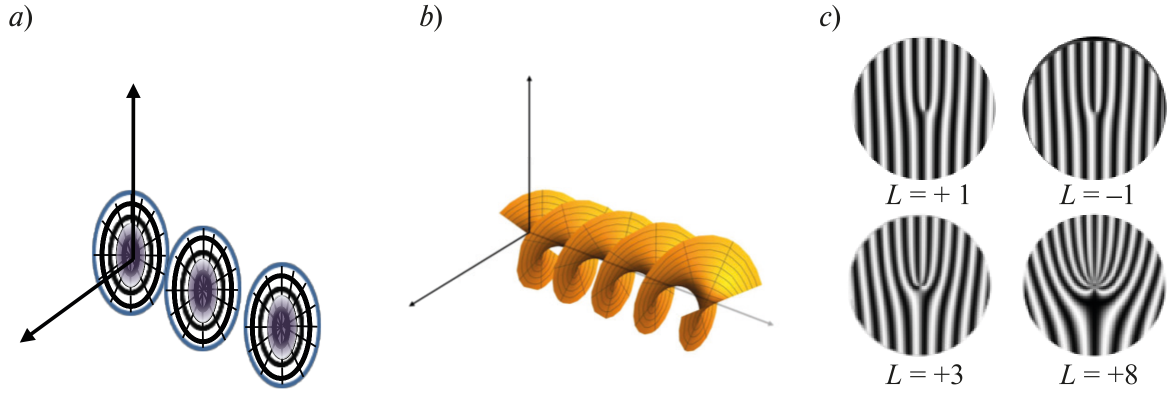

Fig. 1. Phase and intensity front of the initial Gauss beam (*a*); spiral phase front of an OAM carrier (*b*); diffraction patterns for $L = \pm1, +3, +8$ (*c*)

corresponds to a specific charge [8]. Diffraction of a wave on such masks changes its topological charge, for example, diffraction of a plane wave produces waves with OAM, while diffraction of an OAM wave can result in a plane wave.

In general, a grating with $+L$ transforms the initial Gaussian beam into a diffracted one, where the zero's (central) diffraction order keeps with topological charge of the initial beam, the first (right) diffraction order has the same L as the grating, the minus first (left) diffraction order has $-L$, and each subsequent order changes the topological charge by $+L$ or $-L$. The charge of each subsequent order increases due to a specific pattern: the lines bend more and more in the direction from the center of the pattern. Therefore, the size of gratings must be comparable to the width of the original beam, such that the beam passes through it entirely.

One of the significant advantages of this method is that the same gratings are used to detect OAM in the received beam. To detect an OAM beam, it is sufficient to transform it back into the original Gaussian beam [6]. To do this with help of forked holographic gratings, it is necessary to select the first diffraction order with $+L$ (as its topological charge is equal to the charge to which the pattern corresponds) and let it pass through the plate with a charge equal to $-L$, in other words, the inverted one [5, 9]. Topological charge of the resultant beam becomes 0, which means it turns back into the Gaussian beam. Since our grating is made of a reflective material, the pattern formed by the slotted lattice can be considered as inverted at the reflection.

Experimental Setup

The diffraction patterns were cut on the niobium plates on a sapphire substrate. For this experiment, gratings with patterns corresponding to $L = \pm1, \pm3, \pm8$ are used. Each pattern is produced in slightly different sizes for greater measurement accuracy. Gratings of 0.3 mm in size (denoted as Grid 1 in Fig. 2,*a*) were used to generate OAM, and of 0.2 mm (denoted as Grid 2 in Fig. 2,*a*) to detect it. When passing through a large lattice, the rays are more intense, which simplifies the detection process, as well as the resulting pattern has less artifacts (side spots) around diffraction orders.

The source of the Gaussian beam was a red free-space CW laser at 650 nm (Fig. 2,*a*). The beam fell orthogonally on the first grating, transforming into a diffraction pattern at its output. The first right order was selected on the obtained picture and guided through the diaphragm to block all other orders and then was focused by converging lens (F = 40 mm) and completely reflected from the second grid which detects OAM.

In the measurement process, an important condition for observing the proper image is to maintain the straight direction of the beam after passing through the first grating, the diaphragm, and the lens (the same applies to the reflection from the second grating). Otherwise, there will be distortions of the pattern and even the absence of some orders during the detection.

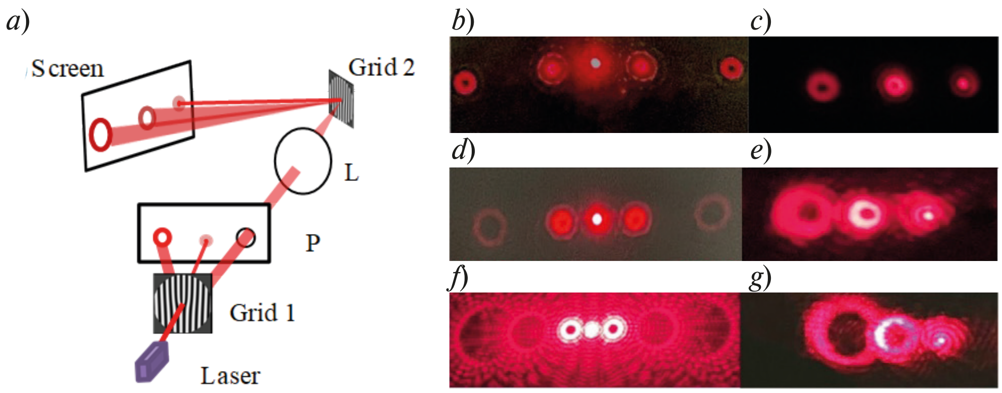

Fig.2 Experimental setup: laser, first grating Grid 1 (L = +1, +3, +8), pinhole P, converging lens L, second grating Grid 2 (L = -1, -3, -8) (*a*); pattern generated by grating with L = +1 (*b*); pattern formed by detected beam (L = +1) after reflection from second grating of the same charge (*c*); pattern generated by grating with L = +3 (*d*); detected beam with L = +3 (*e*); pattern generated by grating with L = +8 (*f*); detected beam with L =+8 (*g*)

Results and discussion

After passing through the first grating, the Gaussian beam transforms into the required diffraction pattern (Fig. 2,*b*): at the central order we have $L = 0$, so the beam remains Gaussian, the right order has charge $+l$, the left order has charge $-l$. The fact that the charges of the first orders have equal charge magnitude can be confirmed by comparing the size of the dark "core" of the beams. Each subsequent diffraction order has lower intensity (thus we select the first order), a larger size and a smaller width of the "ring" itself, which confirms that the topological charge increased with each order. The larger L of the lattice, the faster topological charge increases with each order (Fig. 2, *d*, *f*).

When the selected order is focused on the second lattice and reflected from it, it forms a new pattern (Fig. 2, *c*, *e*, *g*). The central order keeps the charge of the original beam (in our case, $L = +1, +3, +8$). In the left, its charge modulus increases by L of the grating, and in the first right order the beam becomes Gaussian back and thus his OAM is detected. This can also be judged by how the intensity is distributed: in the resulting pattern, the Gaussian beam is not the brightest, and the brightness decreases with each order starting from the first. Summarizing all these facts, it can be concluded that the efficiency of generating OAM beams with topological charges of +1, +3 and +8 is proven experimentally.

Conclusion and Outlook

Results of our experiment confirms the possibility of generation and detection of OAM light beams via the forked diffraction method. This method significantly simplifies the study and the use of OAM beams, and enables numerous applications, e.g., quantum communication protocols and molecule identification in biochemistry [7], to name a few. Now, we have shown OAM beams with an integer topological charge. In future, we also consider manipulations with superpositions of two different OAM charges, low light intensity at the level of single photons, and the use of OAM photons in the field of quantum communications.

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REFERENCES

1. **Sych D., Grishanin B., Zadkov V.,** Critical error rate of quantum-key-distribution protocols versus the size and dimensionality of the quantum alphabet November 2004 Physical Review A 0523312.

2. **Sych D., Grishanin B., Zadkov V.,** Analysis of limiting information characteristics of quantum-cryptography protocols, Quantum electronics. 35 (1) (2005) 80–84.

3. **Sych D., Grishanin B., Zadkov V.,** Quantum key distribution with a continuous alhabet, Laser Physics. 14 (10) (2004) 1314–1321.

4. **Sych D., Leuchs G.,** Quantum key distribution with multi letter alphabets, Optics and spectroscopy. 108 (April) (2010) 326–330.

5. **Chen R., Zhou H., Moretti M., Wang X., Li J.,** Orbital Angular Momentum Waves: Generation, Detection and Emerging Applications, IEEE Communication Surveys & Tutorials. 22 (November) (2019) 840–868.

6. **Allen L., Beijersbregen M B., Spreeuw R.J. C., Woerdman J. P.,** Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes, Physical Review. A 45 (1992) (11).

7. **Stepanov I. V., Fatkhiev D. M., Lyubopytov V. S., Kutluyarov R. V., Grakhova E. P., Neumann N., Khonina S. N. Sultanov A. K.,** Wavelength-Tunable Vortex Beam Emitter Based on Silicon Micro-Ring with PN Depletion Diode, Sensors. 22(3) (2022) 929.

8. **Mair A., Vaziri A., Weihs G., Zeilinger A.,** Entanglement of Orbital Angular Momentum States of Photons, Nature. 412 (6844) (2001) 313–316.

9. **Cunha A. B., Figueira G., André P. S.,** Generation of Orbital Angular Momentum Beams November 2015 CONF TELE 2015, Aveiro, 108.

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