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Formation of second order optical vortices with a radial polarization converter using the double-pass technique

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ABSTRACT

In this paper we both theoretically and experimentally demonstrate possibility to form double charged optical vortex using only one S-waveplate in double-pass geometry. The experimental results are presented as well as analysis of underlying theoretical principles.

1. Introduction

Dislocations in wavefronts were first discovered in 1974 by Nye and Berry [1]. Although their experiment was with ultrasonic waves, the concept applies to optical waves as well. One type of such dislocations, the screw dislocation, in optical waves is known as an “optical vortex” (OV) [2]. It is a line in space, on which the phase is undefined and the intensity is zero, as opposed to the case when the Gaussian beam is covered and the Poisson spot would be visible in the far field. Around the dislocation is the spiral phase ramp, along which the phase grows by $\Delta\Phi = 2\pi l$, where l is the “topological charge”. The wave front around such dislocation is helical in geometry, its helicity described by the modulus and the winding direction by the sign of topological charge.

Due to their remarkable properties, OVs have found numerous applications in science and technology, such as, for example, the OV coronagraph [3], optical tweezers [4], STED microscopy [5] and microtube fabrication using the nanopolymerization technique [6].

Since the OVs are useful in many practical applications, numerous ways have been invented to generate them, each with its own benefits and drawbacks. One of the simplest methods, also one of the earliest ones is to use a computer-generated hologram [7–13]. This method is cheap and simple, since the holograms can be printed on a transparent film with a high-resolution printer. This method allows the formation of OVs of predefined topological charge. However, such holograms have a very low efficiency, since most of the power goes into the zero-order maximum and higher order OVs. In addition to this, such printed holograms have a very low optical damage threshold, thus making it impossible to obtain high-power OVs. Another possibility is to use the phase plates [14], however they are difficult to manufacture. It is also possible to generate OVs with a spatial light modulator [15] or deformable mirror arrays [16].

Other approaches have also been suggested, such as creation of OVs by laser and other resonator systems [2,17–20], cylindrical lens mode converter [21,22] and by using hollow micro-spheres, fabricated inside glass [23]. However, such methods are extremely complicated, some of them requiring very high precision and stability of the optical system.

A new method for OV generation has been recently discovered that is both simple and not limited by optical damage threshold, unlike printed holograms or spatial light modulators. It has been shown that a radial polarization converter (the “S-waveplate”) [24,25] can produce OVs with topological charge $|l| = 1$ from circularly polarized light [24,26]. It is also possible to form $|l| = 1/2$ vortices using a different wavelength than the S-waveplate's (SW) native wavelength [26]. In this paper, we demonstrate a possibility to generate OVs with topological charge $|l| = 2$ using the SW in the double-pass setup. We present theoretical explanation of this technique and numerical simulations as well as the experimental results.

The paper is organized as follows: Section 2.1 gives a brief overview of the SW's operation and its effect on OV, Section 2.2

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gives overview of the theoretical principles underlying the double-pass technique, Section 2.3 gives suggestions on how to extend the technique for vortices of larger topological charge and Section 2.4 shows results of numerical simulations of the double-pass scheme. We show that the results of the practical implementation of the double pass scheme are shown in the experimental section, certain technical details are explained as well. Conversion efficiency issues are also discussed.

2. Theoretical

In this section the basic principles of the double-pass technique are explained theoretically. Basics of the SW operation are explained in Section 2.1, and the idea of the double-pass setup is presented in Section 2.2. In Section 2.3, the possibility to extend this method to larger topological charges is discussed and in Section 2.4, results of numerical simulations are presented.

2.1. Operation of the S-waveplate

The SW is manufactured by direct laser writing in silica glass [24,25]. By irradiating the volume of glass with ultrashort laser pulses, sub-wavelength nanogratings can be formed [27], which act as a birefringent medium [24], thus altering the polarization of passing light.

The nanogratings have two periodicities: perpendicular and parallel to the light polarization direction. These nanogratings have sub-wavelength periods, therefore they alter the refractive index for the light. The polarization components polarized parallel to the interfaces of gratings experience a larger refractive index than those polarized perpendicular to them. This is how the birefringence manifests.

By distributing such gratings within the volume of glass, complex polarization elements can be formed [24,25]. The SW is formed in such a way that the orientation of these nanogratings depends on the azimuthal angle. In other words, it is a $\lambda/2$ waveplate with varying direction of principal axes (Fig. 1). When a linearly polarized beam goes through such plate, its polarization becomes inhomogeneous. This way the cylindrical vector beams are formed: the radial or azimuthal polarization beams (depending on the polarization of the incident light) or a superposition of both.

It is also known that when a Gaussian beam with a circular polarization goes through the SW, a circularly polarized OV with topological charge $|l| = 1$ is formed. The polarization handedness of this OV is opposite to that of the incident beam [24,26]. It has been shown in [24,26] that the Jones matrix of the SW is

$$\hat{J}_{SW} = \begin{bmatrix} \cos\phi & \sin\phi \\ \sin\phi & -\cos\phi \end{bmatrix}. \tag{1}$$

Multiplied by circular polarization vector, we obtain azimuthal phase dependency of the resulting beam:

$$\vec{w} = \frac{1}{\sqrt{2}} \begin{bmatrix} \cos\phi & \sin\phi \\ \sin\phi & -\cos\phi \end{bmatrix} \begin{bmatrix} 1 \\ i \end{bmatrix} = \begin{bmatrix} 1 \\ -i \end{bmatrix} \frac{e^{i\phi}}{\sqrt{2}}. \tag{2}$$

As can be seen from Eq. (2), the resulting beam has a phase factor $e^{i\phi}$, which is a characteristic of an OV, and a circular polarization of opposite handedness than that of incoming beam.

Eq. (2) shows how the SW acts on a simple circular polarization beam. If it is to be used in double-pass scheme, its effect on an OV must be investigated. Therefore, we consider a circularly polarized OV of arbitrary topological charge l and polarization handedness, passing through the SW. The amplitude of the initial OV is given in the following equation:

$$\vec{v}(\rho, \phi) = A_l(\rho) \begin{bmatrix} 1 \\ \pm i \end{bmatrix} e^{il\phi}. \tag{3}$$

$A_l(\rho)$ is the envelope function. The polarization with vector $[1, i]$ will be called clockwise (CW) and the reverse polarization $[1, -i]$ – counter-clockwise (CCW). The resulting beam is simply obtained by multiplying the Jones matrix (Eq. (1)) by the incoming beam (Eq. (3)):

$$\vec{w}(\rho, \phi) = \hat{J}_{SW}(\phi)\vec{v}(\rho, \phi) = A_l(\rho) \begin{bmatrix} \cos\phi \pm i\sin\phi \\ \sin\phi \mp i\cos\phi \end{bmatrix} e^{il\phi}. \tag{4}$$

The result of Eq. (4) can be rewritten as

$$\vec{w}(\rho, \phi) = A_l(\rho) \begin{bmatrix} 1 \\ \mp i \end{bmatrix} e^{i(l\pm 1)\phi}. \tag{5}$$

From Eq. (5) we can see that the polarization changes handedness (compared to Eq. (3)) and, depending on polarization of initial beam, the topological charge changes (increases or decreases by 1). We introduce a polarization factor $p = \pm 1$ to denote the handedness of polarization ($+1$ – CW, -1 – CCW). The modulus of topological charge $|l|$ will be increased when the polarization handedness of the incoming beam coincides with the handedness of the helical wavefront. If we denote the topological charge of the resulting beam as m, the modulus of this topological charge will be

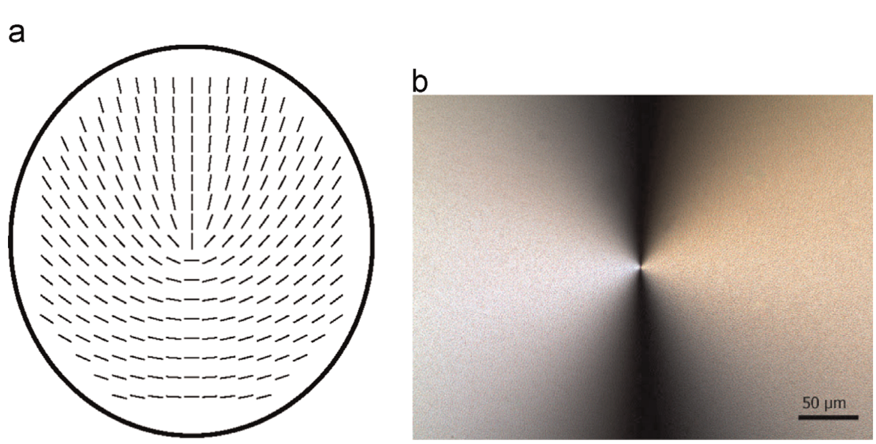

Fig. 1. The S-waveplate (radial polarization converter) consists of many birefringent nanogratings, formed by irradiation of silica glass by ultrashort laser pulses [24,27]. (a) Orientations of nanogratings distributed in the volume of an S-waveplate, (b) photo of an S-waveplate between crossed polarizers.

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