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Transformation of the vortex beam in the optical vortex scanning microscope

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ABSTRACT

We investigate the microscopic system in which the Gaussian beam with embedded optical vortex is used. The optical vortex is introduced by vortex lens. The vortex lens shift induces a precise nanometer shift of the embedded vortices inside the focused spot. The analytical formula for the complex amplitude of the focused spot with off-axis vortex was calculated, to our knowledge, for the first time. This solution is an important step in the development of the optical vortex scanning microscope. Experimental results are also presented that demonstrate the behavior of such a beam in an experimental setup.

1. Introduction

Laser beams carrying optical vortices (vortex beams) are extensively studied from both the fundamental and practical reasons [1,2]. The vortex beam is widely used in such areas as optical trapping [3], optical imaging and measurement [4–10], manufacturing [11]. Since the papers published by Tychynsky [12,13] the stable optical phase dislocations (optical vortices, in particular) are used to find a route to superresolution microscopy. The Tychynsky project failed, mainly for the reasons explained in [14]. Nevertheless, some new solutions for superresolution with optical vortices were proposed in papers [15–20]. Also the effect of superoscilations provided a new theoretical insight into the problem of superresolution with the vortex beams [21,22].

Our present system of the Optical Vortex Scanning Microscope (OVSM) is a development of the solution presented in papers [23–26]. We propose to use a beam with the embedded vortex in the imaging system. The beam is focused on the sample, which lays on a motorized table for scanning. After interacting with the sample, the optical vortex changes its position and its internal structure that is the phase geometry around the vortex point (i.e. point where the phase is singular). Additionally we proposed to move the vortex inside the beam, giving the possibility of scanning the sample by vortex point itself (the method is called-internal scanning method [23]). In practice the system was constructed in the following manner (Fig. 1). An optical vortex was introduced into the He-Ne laser beam by the spiral phase plate (vortex lens [1,27]) and focused by the microscope objective into the sample plane. The phase plate was mounted on a motorized stage and was moved in the direction perpendicular to the optical axis. As a result the vortex point moved at the sample plane. To find the vortex trajectory the Fresnel diffraction integral was solved for the problem illustrated in Fig. 1 [23,24]. As a result we get the following formulas.

$$x(z) = -x_c z_0\left(\frac{1}{R(z)} + \frac{1}{f}\right) + x_c, \tag{1a}$$

$$y(z) = -2\frac{z_o}{kw^2(z)}x_c, \tag{1b}$$

where f is the focal length of the len, x_c is a shift of the phase plate and:

$$w^2(z) = w_o^2\left(1 + \left(\frac{\lambda z}{\pi w_0^2}\right)^2\right), \tag{2a}$$

$$R(z) = z\left(1 + \left(\frac{\pi w_0^2}{\lambda z}\right)^2\right). \tag{2b}$$

Here w_0 is a Gaussian beam waist and z is a distance between the waist plane and the vortex lens plane.

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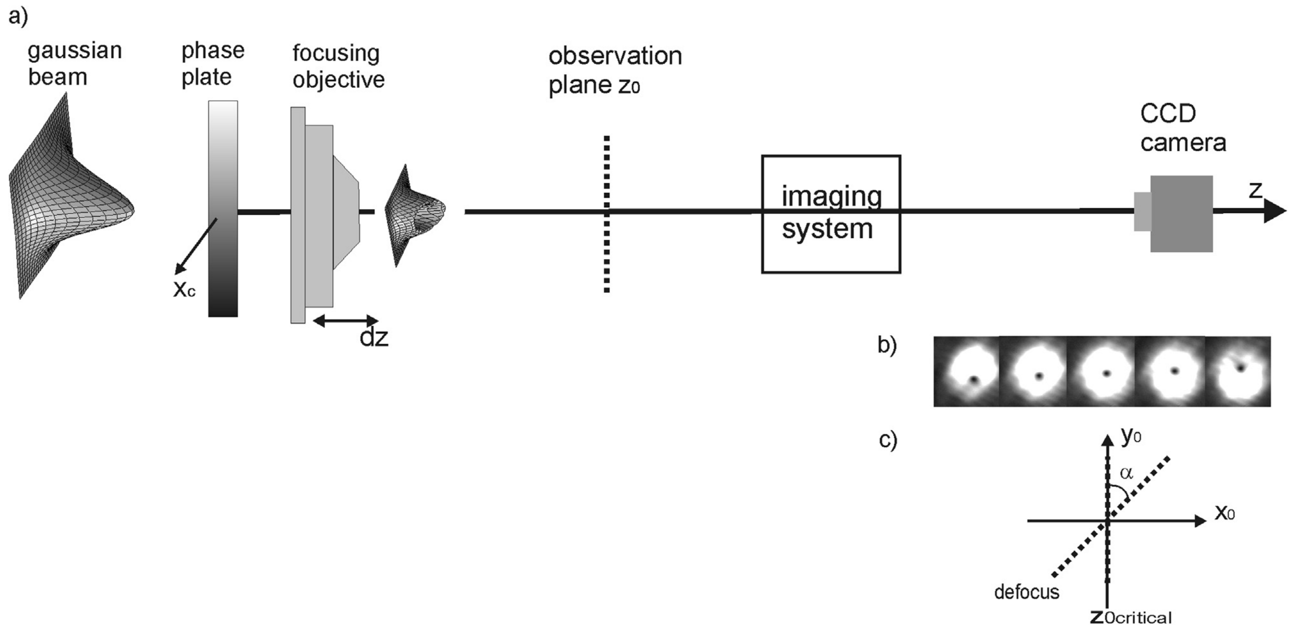

Fig. 1. (a) Scheme of the experimental set-up, (b) exemplary diffraction images detected on the CCD for five different phase plate shifts, (c) as the vortex is moved, its position can be found and its trajectory determined, trajectory angle α varies depending on the position of the observation plane.

Formulas (1) show that shifting the vortex lens along a straight line causes the movement of the optical vortex (at the observation plane) also along a straight line and the orientation of the vortex trajectory depends on the position of the observation plane (Fig. 1). There exists such an observation plane position, where the vortex trajectory is perpendicular to the direction of the vortex lens shift. We called it a critical plane. The critical plane position can be found from the formula [24].

$$z_{crit} = \frac{R(z)}{R(z)+f}f \tag{3}$$

Since the optical vortex sensitivity, to any phase changes, is highest at this plane [24,25], the sample under investigation should be put there. This sensitivity is far enough for super-resolution imaging.

The experiments reported in our previous papers together with numerical simulations allows to find prescriptions for measuring the features of well defined simple objects. We can measure the position of the phase step, phase row width, grating period with the resolution exceeding classical limit. Nevertheless, with these prescriptions the usability of the OVSM is very limited. To find the effective procedures for computing the sample topography from the measured vortex phase profiles the full analytical model of the basic OVSM optical path has to be determined. This path is illustrated in Fig. 1. It can be considered as the simplest OVSM version (with no reference beam). The whole system is described in [26]. The analytical model was built in three steps. In the first step an exact formula for the focused laser beam with shifted optical vortex was derived. In the second step the propagation of such a focused beam through the imaging system of the OVSM was calculated. In the third step the simple objects were added at the OVSM's sample plane and the Fresnel diffraction integral was solved. Since the calculations are large each step will be presented and discussed in the separate paper. In this paper we discuss the results obtained in the first step. The formulas (1) were derived under assumption that the vortex lens shift x_c is small and they are valid close to the optical axis. Consequently we cannot reconstruct the complex amplitude of the whole focused vortex beam. So we need to solve the corresponding Fresnel diffraction integral with no simplifications.

The propagation of vortex beam with broken symmetry has become a topic of many research papers in the last decade. Dennis et al. analyzed the problem of splitting higher order vortices under dielectric reflection by an oblique angle [28,29]. Beksheav et al. investigated the effect of misalignments of holograms used for OV generation [30,31]. Singh et al. studied the influence of aberration on the optical vortex phase profile and position [32,33]. The results presented in this paper are new and have a fundamental meaning for understanding the imaging with the OVSM. In particular, the full analytical solution of the laser beam propagating through the focusing optical system with off axis higher order vortex lens was derived and discussed, for the first time.

The common way of solving the difficult diffraction problems is a stationary phase method [34]. For large wave number k, as it is in optics, highly oscillating terms contributes at a very small rate and can be omitted. We tried this method for solving our problem, but with negative result. The subtle dynamics of the optical vortex was lost. This is due to very low light intensity and fast changing phase in the vicinity of the vortex point, so even a small contributions cannot be neglected. In paper [35] the problem of vortex beam propagated through axicon was solved with the use of stationary phase method. However, the case studied in that paper had full radial symmetry. When the symmetry is broken the stationary phase method does not reproduce the optical vortex dynamics.

2. Analytical solution

We want to solve the following problem. Gaussian beam with the complex amplitude.

$$u_g(x, y) = \exp\left\{-\left(\frac{1}{w^2(z)} + i\frac{k}{2R(z)}\right)\left(x^2+y^2\right) + i\zeta(z)\right\} \tag{4}$$

goes through the shifted by x_c vortex lens with the phase profile.

$$t_v(x, y) = \exp(\mathrm{im}\, Arg(x+iy)) \tag{5}$$

(m is a topological charge of the optical vortex to be generated) and then it is transformed by the lens with the transmittance function: