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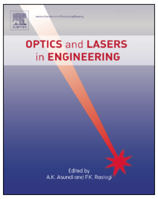

Optical Vortex Scanning in an aperture limited system

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ABSTRACT

We consider an optical system that consists of a vortex lens and a microscopic objective. The system is illuminated with a He–Ne laser. In our previous work we showed that moving the vortex lens perpendicularly to the optical axis makes the optical vortex (introduced by the vortex lens) move inside the focused beam in a characteristic way. We also showed that the vortex trajectory is very sensitive to the position of the observation plane, especially for a large diameter of the incident beam. However, in the microscopic system the aperture is limited by the microscopic objective. In this paper we investigate the propagation of the wide incident laser beam through a vortex lens and then through a microscopic objective with small aperture. We also present a fast interferometric technique for the phase pattern reconstruction of the focused vortex beam.

1. Introduction

There are a number of ideas concerning the use of optical vortices in microscopy. Most of them are focused on improving the resolution of microscopic systems. The first solution was suggested by Tychinsky et al. [1–3]. Tychinsky proposed to measure the phase dislocations propagating within the zero diffraction order beam. The dislocations were born due to light reflection from the sample. The beam was highly magnified (up to 10,000 ×) and interfered with a reference beam whose phase was controlled by a moving mirror (phase shifting interferometry). Despite the extensive research work in this direction the whole project was not successful [4]. A new design for vortex microscopy was suggested in [5]. The vortex beam was introduced into the scanning beam and observed after passing through the sample. This solution was named Optical Vortex Scanning Microscopy (OVSM). The system was applied for quality assessment of micro-samples with side walls of a few hundreds of microns depth [6] and for establishing the position of a sub-λ phase step with resolution exceeding the classical limit [7]. In both cases the number and trajectory of optical vortices were controlled to measure the desired sample parameters. The concept was also shared by Spector et al. [8,9]. However, Spector measured the total light intensity in a small region around the central part of the image. These results are interesting but not satisfying. The OVSM was used for very specific tasks like inspecting the side walls' quality of deep micro-structures or finding a phase step's position. More complicated objects result in more complicated images, which could not be analyzed in the way presented in the previous works. A new idea was necessary to keep the OVSM project alive.

Such an idea emerged as a result of investigating a new scanning method. Instead of moving the whole beam or a sample this new scanning method is based on a vortex generator shift [10,11]. By a vortex generator we mean an element designed for introducing an optical vortex into a laser beam. In [10] a spatial light modulator and in [11] a spiral phase plate (vortex lens [12–15]) were used as a vortex generator (Fig. 1). When the vortex lens moves, the dark point (vortex point [16–20]) located inside the focused optical vortex beam (i.e. a beam carrying an optical vortex) moves in the observation plane. Obviously the vortex point can be localized with a limited but sufficient accuracy in the experiment [21,22].

The optical vortex response to the vortex lens shift reveals an interesting feature which can be used for high resolution imaging. According to the analytical formulas presented in [10,11], the optical vortex shift can be described as follows:

$$x_o = x_c(1 - z_o g(z)) \tag{1a}$$

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

$$g(z) = \frac{1}{R(z)} + \frac{1}{f} \tag{1c}$$

where x_o and y_o are coordinates of the vortex point at the observation plane, x_c is the vortex lens shift, f is the focal length

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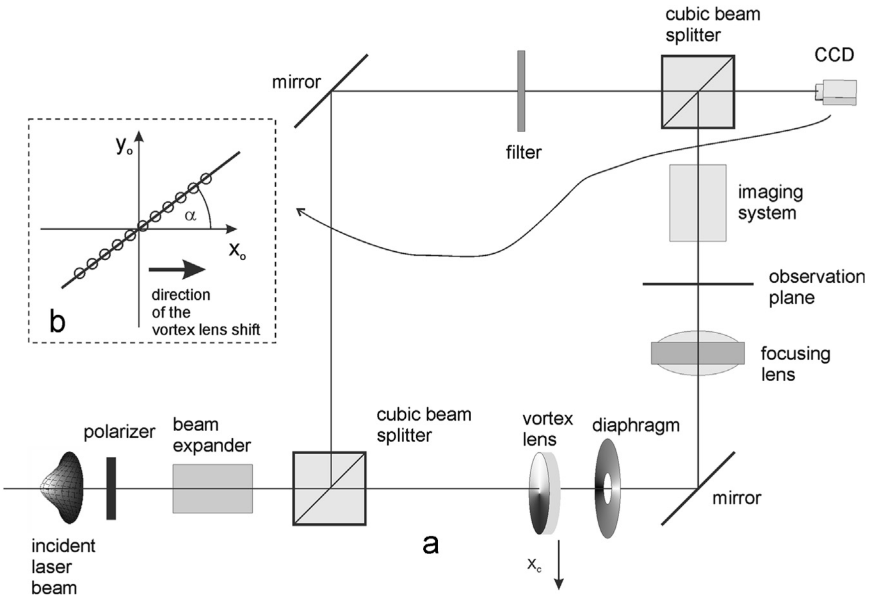

Fig. 1. The scheme of the experimental setup. (a) The general view and (b) the rectangular window in the upper left corner shows the coordinates system at the CCD camera. The measured position of the vortex point is illustrated by the set of circles. The solid line (vortex trajectory) illustrates the fitted curve to these points.

of the focusing lens, $w(z)$ is the Gaussian beam radius at the vortex lens, $R(z)$ is the Gaussian wavefront radius, z is a distance between the beam waist and the vortex lens plane, and z_o is the distance between the vortex lens and the observation plane. The above formulas were derived under a few additional assumptions which conformed well to the experimental conditions. It was assumed that the vortex shift x_c as well as the area of interest at the image plane was small; hence the terms including x_c and ρ (radial coordinate in the image plane) with powers 2 and higher were neglected. Since the microscopic objectives of small numerical aperture (NA <0.25) were used in the experiment the polarization and aberration effects on the focused vortex beam [23–25] were neglected.

Formulas (1) mean that if the vortex lens moves along a straight line the vortex point also shows a similar movement. However, the range of this movement is different and the trajectory line is inclined at various angles α depending on the z_o position of the image plane (Fig. 1). The α angle is defined by

$$\alpha=\arctan\frac{y_o}{x_o}=\arctan\frac{2}{k\,w^2(z)((1/z_o)-g(z))}\tag{2}$$

There is also a special position defined by

$$\frac{1}{z_o}=g(z)\tag{3}$$

where the optical vortex moves perpendicularly to the vortex lens shift ($x_o=0$ and $\alpha=\pi/2$). The observation plane located at this position is called the critical plane (z_{crit}). The angle α changes rapidly in the vicinity of the critical plane which is well illustrated by its derivative as a function of z_o:

$$\alpha'(z_o)=\frac{2\,k\,w^2(z)}{4\,z_o^2+k^2\,w^4(z)(1-g(z)z_o)^2}\tag{4}$$

At the critical plane ($z_o=z_{crit}$) this derivative takes the value

$$\alpha'_{crit}(w)=\frac{k\,w^2}{2\,z_{crit}^2(w)}\tag{5}$$

Fig. 2 shows a plot of Expression (4). The function $\alpha'(z_o)$ has a narrow peak located at z_{crit}. It is worth noticing that there is a strong relation between the peak value and the beam waist (5). For example, changing the value of the beam waist 4 times increases the peak value of α' by 12 times for the focusing lens with focal length $f=50$ mm and 11 times for the focusing lens with $f=10$ mm. It means that with increasing radius of the incoming laser beam the changes of trajectory angle α become faster in the vicinity of the critical plane. These changes are well characterized by the FWHM (Full Width at Half Maximum) parameter, which can be calculated by

$$H=4\frac{\sqrt{k^2w^2(z)z_c^4+8z_c^6}}{k^2w^2(z)+4z_c^2}\tag{6}$$

Formula (6) was derived by combining Formulas (4) and (5).

The optical vortices can be generated by special computer-generated holograms [26,27]. In the papers [28,29] the question of vortex point's position in the case of transversely shifted and inclined holograms was investigated. In such situations the vortex point is displaced orthogonally to the hologram shift. Since no focusing element was used a comparison with our results is not possible.

We pointed out in paper [11] that the vortex point trajectory is sensitive to the presence of a sub-λ phase step when the phase step is located close to the critical plane. This sensitivity is due to a beam radius difference on both sides of the step, which in turn means that the vortex point on both step sides tends to move in two different directions (Fig. 3). The effect can be used to develop super-resolution microscopy. It was shown in paper [30] that the possible small errors resulting from the vortex lens manufacturing or system's misalignment were not harmful for the new OVSM project.

The present paper is organized as follows. In Section 2 the following issue is investigated. Fig. 2 shows that the vortex trajectory angle changes faster for larger radius $w(z)$ of the incident laser beam and smaller focal length of the focusing lens. Small focal length means that in the real system this is a microscopic objective with relatively small aperture. Thus after passing the vortex lens the beam radius is reduced. There are two questions to be answered:

a) What is the vortex trajectory sensitivity when the radius of the beam $w(z)$ passing through the vortex lens is reduced by the microscopic objective?