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Internal scanning method as unique imaging method of optical vortex scanning microscope

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ABSTRACT

The internal scanning method is specific for the optical vortex microscope. It allows to move the vortex point inside the focused vortex beam with nanometer resolution while the whole beam stays in place. Thus the sample illuminated by the focused vortex beam can be scanned just by the vortex point. We show that this method enables high resolution imaging. The paper presents the preliminary experimental results obtained with the first basic image recovery procedure. A prospect of developing more powerful tools for topography recovery with the optical vortex scanning microscope is discussed shortly.

1. Introduction

The idea of superresolution microscopy using phase singularities has been suggested more than 25 years ago by Tychynsky [1–4]. Although the solution proposed by Tychynsky was not successful [5], the phase singularities are still believed to constitute a potential solution for new imaging microscopic systems [6–27] (not all of them are focused on superresolution [9,10,12,13,15,16], papers [23–24] are focused on superlocalization and paper [25] refers to the theory of superroscilatons [26–27]).

The beam with optical vortex reveals a characteristic spiral shape of the wavefront [28–29]. During propagation the phase rotates around a line where its value is undefined. At the screen the line becomes a point (vortex point) (Fig. 1a). The beam carrying optical vortices (vortex beam) possesses some interesting physical features. One of them is the intensity distribution which has a doughnut form (Fig. 1b, the other name for a vortex beam is a doughnut beam). In the intensity pattern one can observe the dark area (vortex core) surrounded by the bright ring. Another characteristic feature is a phase distribution (Fig. 1a).

In the optical vortex scanning microscope (OVSM) we propose to use the focused vortex beam to illuminate the sample. In this kind of illumination, within the area of the vortex core, each sample point is uniquely marked by both the phase and the amplitude value of the focused vortex beam (Fig. 1). This is not the case when the sample is illuminated with the focused Gaussian beam. The vortex beam additionally contains a special point (vortex point) which is very stable. This vortex point recovers after passing through the object (or after reflection from the object) and changes its positions. Sometimes the new vortex twins are born [30–32]. But when the object is scanned with small steps, the original vortex (i.e. vortex introduced by the beam) can be traced. The relation between the positions at which the vortex point hits the detector with and without the sample brings the information about the examined object. These two facts, i.e. the presence of the stable vortex point and the unique mapping of the object by the focused vortex beam (at least inside the vortex core) opens a new opportunity for vortex microscopic imaging. This potential was so far demonstrated for well-defined samples. In paper [17] the method for inspecting a matrix of deep and narrow pillars or wells was discussed. Paper [20] described the supperesolution localization of the single phase step. In the present paper we discuss the question of supperesolution imaging of a wider class of objects. We do not present the ready and universal procedures for vortex image analysis, but rather show that such procedures can be developed.

The OVSM optical scheme is shown in Fig. 2. The illumination source (He–Ne stabilized laser) of the wavelength 633 nm is split by the beam splitter (Bs1) into two arms: the reference and object arm, to construct the Mach–Zehnder interferometer. The object beam passes through the spiral phase plate SPP [33–36]. The SPP has been mounted on the motorized piezo stage, so it could be moved in the direction perpendicular to the optical axis and in this way the internal scanning is performed. Behind SPP the beam carries an optical vortex. Then it is focused by the microscope objective (x10, NA = 0.24, efl = 15.85 mm) to the sample plane. The diameter of the vortex beam at the sample plane is 20 μm and the vortex core diameter equals to 4.5 μm. The image of the sample is relayed to the image plane (CCD) by the 10x microscope objective (NA = 0.24) and the additional lens (efl = 20 mm) which gave the overall magnification of 185x. The reference arm is directed to the CCD camera to create the interference fringes which contain the information about the sample-induced phase shifts. The interferograms with the

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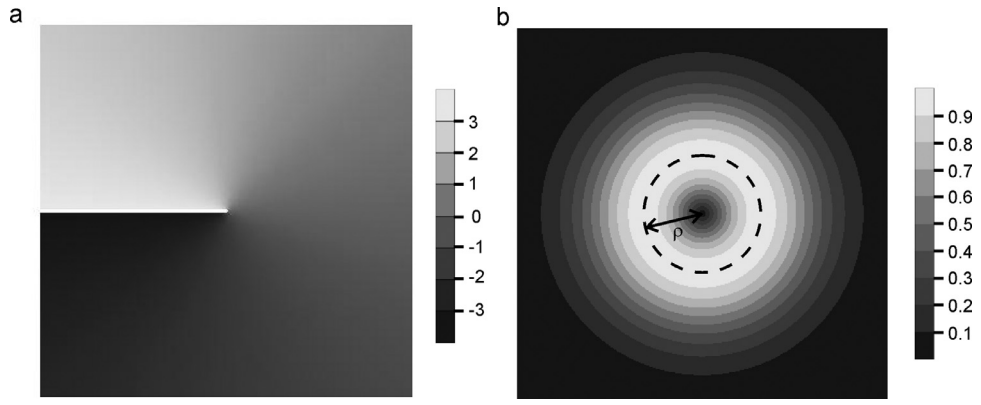

Fig. 1. Phase and amplitude distribution of the vortex beam in a plane cross section. (a) the phase distribution (values are given in radians). The equiphase lines converge to the central point (vortex point), where the phase is undefined; (b) normalized amplitude distribution. There is a dark point (zero amplitude point) at the same location as a vortex point. The symbol ρ denotes the vortex radius (as defined for this paper). The vortex radius is a distance from the vortex point to the circle of the maximum amplitude value (dashed line). The dashed line is a limit of a vortex core area. Each point has a unique complex amplitude value (i.e. phase and amplitude value) inside the vortex core.

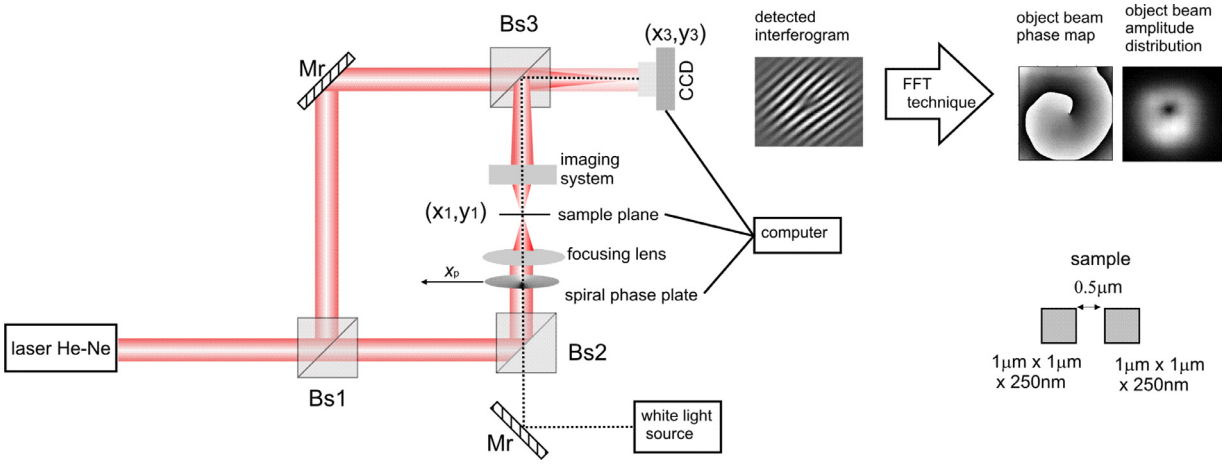

Fig. 2. Scheme of the optical vortex microscope experimental setup. Bs1, Bs2, Bs3 –beam splitters, Mr-mirror, focusing lens-microscope objective NA = 0.24, imaging system –microscope objective NA = 0.24 and the lens with efl = 20 mm. White light path facilitates localization of the sample. The exemplary interferogram and the recovered phase and amplitude maps are shown on the right side, and the schematic presentation of the sample is shown below them.

characteristic fork-like structure (see Fig. 2) are digitally captured by the CCD monochrome camera (1920 × 1200 squared pixels with the size of 5.86 μm). We use the carrier frequency technique [37–38] to reconstruct the phase of the object beam. The spiral shape, characteristic for the vortex beam, is visible in the phase map. Spiral line is a boundary where the 2π jump occurs (see Fig. 2) and the end of the spiral indicates the vortex point position. The position of the vortex point is found directly from the phase map. In the algorithm we look for the correct phase gradient distribution around the given point. This method is so accurate that in our experimental system the vortex localization is limited by the CCD camera's pixel size.

In papers [39–40] the analytical (in scalar approximation) description of the OVSM optical system was presented. The paper [41] enhanced the previous results by adding a simple phase object - SPO. The SPO is a small phase rectangle. With those results, the procedure allowing to reconstruct the phase map of the introduced sample was suggested and tested. Following the [41] complex amplitude of the SPO at the image plane (CCD) u_{im} can be described by the formula

$$u_{im}(x_3,y_3) = a(x_3,y_3)\cdot\exp\{i\varphi(x_3,y_3)\} + a(x_c,y_c)\cdot\exp\{i\varphi(x_c,y_c)\}\cdot[\exp(i\psi)-1] \cdot\Im\left\{\Pi\left(\frac{x_1-x_c}{sx},\frac{y_1-y_c}{sy}\right)\right\} = u_v + u_{Ob} \quad (1)$$

$$u_3(x_3,y_3) = u_v = a(x_3,y_3)\exp\{i\varphi(x_3,y_3)\} \quad (1a)$$

$$u_{ob} = a(x_c,y_c)\exp\{i\varphi(x_c,y_c)\}\cdot(\exp(i\psi)-1) \cdot\Im\left\{\Pi\left(\frac{x_1-x_c}{sx},\frac{y_1-y_c}{sy}\right)\right\} \quad (1b)$$

where x_3, y_3 are coordinates at the image plane, u_3 represents the complex amplitude of the optical vortex beam at the image plane with no object (this term was calculated analytically in [39]), x_c, y_c are coordinates of the SPO center at the sample plane, sx, sy are SPO sizes, ψ is a phase difference introduced by the SPO, $\Im$ represents the transformation of the SPO transmittance function from the sample plane, through imaging unit, to the image plane (this term was calculated analytically in [40]). The larger objects can be decomposed into a sum of the SPO's. The image can be described as a sum [40]

$$u_{im}(x_3,y_3) = a(x_3,y_3)\exp\{i\varphi(x_3,y_3)\} + \sum_{i=1}^{N} a_i(x_{ci},y_{ci})\exp\{i\varphi_i(x_{ci},y_{ci})\}\cdot[\exp(i\psi_i)-1] \cdot\Im\left\{\Pi_i\left(\frac{x_1-x_{ci}}{sx_i},\frac{y_1-y_{ci}}{sy_i}\right)\right\} \quad (2)$$

where a_i is the amplitude of the illuminating beam at the center of ith SPO, φ_i is the phase of the illuminating beam at the center of ith SPO, x_{ci} and y_{ci} are coordinates of the center of ith SPO, sx_i, sy_i are the sizes of the ith SPO and ψ_i is a phase difference introduced by the ith SPO.