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Vortex Interferometric Microscopy with Laguerre-Gaussian Beams

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Abstract

In the present research, we discuss the results of analysis of coherent light beams carrying an optical vortex and propagating through the isotropic medium with a complex surface microrelief and its application to super resolution microscopy. It was shown, that phase analysis of singular beam with single charged centered optical vortex allow to retrieve information about sample surface relief. High spatial resolution caused by vortex helical phase sensitivity to disturbances in wave front after reflection or spreading through studying sample, which can be optically transparent or have a reflecting surface. This method applicable for non-destructive testing of live cells and biological tissues in real-time regime with exceeding optical diffraction limit. Vertical resolution of a microscope based on the phase singularity of Laguerre-Gaussian beams of low order can be achieved down to 5,27 nm for helium-neon laser source for optically transparent and reflecting surfaces.

Keywords: optical vortex, phase, microscopy, singularity

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1. Introduction

The unique properties of optics of singular beams that are able to transform a Gaussian beam into a vortex one [1], control and observe its parameters find a use in different devices for trapping, transportation, and angular orientation of microparticles [2]. Last significant research effort has been invested in its physical implications and possible applications of vortex beams, especially in microscopy and digital imaging [3–5]. There are a great number of articles devoted to the problem of a beam reflecting or transmitting through the observable sample in both coherent and non-coherent light [6–8] for non-contact metrology of nanostructures. Such techniques can be used for controlling of surface profile in various fields of technology, in the debugging of technological processes and in express testing of the final product and in scientific research [9–11].

A class of microscopes-profilometers is known, whose operation is based on the principle of heterodyne interferometry [12]. The heterodyne sensing part as a proposed concept [13] has an imaging system carrying Mach-Zehnder interferometer that measures line-of-sight deformation. In summarize, a coherent probe beam reflected from a test surface and interfered with a reference beam on a CCD camera. The probe and reference beams have slightly different optical frequencies and the resulting temporally beating intensity signal on the CCD camera is sampled and stored for each pixel. A phase value was computed for point of image using a simple Fourier coefficient-based algorithm. The known heterodyne surface profile analyzers are distinguished by the values of difference in the frequencies of laser beams, and by the specific parameters of optical elements. As an another alternative, the full-field interferometric microscopy was proposed. This method combine two-wavelength interferometry and heterodyne interferometry [14], where was used a modified Twyman–Green interferometer. The sampled intensities was recorded by each pixel of CMOS camera, then the phase of reference point and the relative phase of the captured image are compared and calculated. The same measurement was performed again for different wavelengths. Further improvement of this technique was embodied by single-shot multiwavelength interferometry [15]. However, despite these measures, the accuracy of the heterodyne detector has limitation because of the difficulty of maintaining a close-frequency difference with high stability. Thus, the actual task of searching effective and fast methods for microscopy application is opened.

A well-known practical application of optical vortex in the vortex scanning optical imaging allows to study, for example, the surface geometry and optical density of the sample by analysis of phase singularity's distortion [16]. Also, it was shown that vortex phase analysis carrier information about topology of surface, and depends of the features of incident beam and different aperture of optical systems [17]. In manuscripts [18–20] authors developed a new solution called Optical Vortex Scanning microscope where the sample is scanned by moving vortex lens producing a vortex movement inside the beam by characteristic way. This study demonstrates the response of the optical vortex imbedded in focused Gaussian beam to the phase steps inside the object arm of interferometer. Scanning of sample enables to plot a vortex trajectory, which has a different inclination angles to the direction of vortex lens movement and depends on thickness of the probe. Further research of Optical Vortex Scanning Microscope conducted with developing of analytical models and phase retrieval algorithms [21, 22].The last investigation [23] describe both theoretical and experimental results of imaging system using movable optical vortex, where the image of the probe was combined with the structure of the vortex beam. Nevertheless, the phase distribution after the object may recovered with quite good accuracy, thus the model of the Optical Vortex Scanning Microscope opens new possibilities for the development of reconstruction procedures and for optical system optimization.

In the present research we focus our attention on the interferometry analysis of phase evolution of light beam carrying axial optical vortex and its application to microscopy without any additional scanning methods and movable vortex lens. This technique is able to perform measurements of thickness and surface topology without direct contact with an object in non-destructive way with high accuracy.

2. Materials and methods

Let us consider the propagation of the paraxial beam along the z-axis. The transverse E_x component have a wavenumber$k_x = nk_o$, where k_o is a wavenumber in a free space and $n = \sqrt{\epsilon}$ – refractivity index of a test sample. In the paraxial approximation, we can treat the linearly polarised component as $E = \tilde{E}_x(x, y, z)\,\text{exp}(-ik_x z)$. Then, the paraxial equations for the complex amplitude $\tilde{E}_x$ can be represented in the form [29]:

$$d_x^2 \tilde{E}_x + d_y^2 \tilde{E}_x - 2ik_x d_z \tilde{E}_x = 0. \tag{1}$$

A particular solution to the paraxial wave equation (1) for the vortex beam we can write in the reference frame *x, y, z* of the sample:

$$\tilde{E}_x = \left(\frac{x - i\xi\, y}{w_o \sigma_o} \right) \times \text{exp} \left[- \left(x^2 + y^2 \right) / w_o^2 \sigma_o \right] / \sigma_o, \tag{2}$$

where:$\sigma_o = \frac{1 - i\, z}{z_o}$, $z_o = \frac{nkw_o^2}{2}$, w_o – is the radius of the beam waist at the sample plane ($z = 0$), $\xi = \pm 1$ – is the vortex topological charge. The vortex state is described by the equation $Re\tilde{E}_x(x, y,\ z) = Im\tilde{E}_x(x, y,\ z) = 0$. In such wise, the main parameters used for optical microscope are: w_o – waist radius, z – thickness of explored sample and n – refractivity index for transparent materials.

Numerical calculation of interference pattern accordingly to the second term in equation (2) of beam carrying optical vortex, the well-known Laguerre-Gaussian beam with typical spiral in case of axial interfering beams and "fork"-shaped interference fringes for inclined reference beam are shown in Figure 1 (a, b). Phase of centered vortex beam is shown in Figure 1 (c).

As we can note from the Figure 1, phase patterns of helical shape show a rotation caused by optical path difference. Observable rotation is quite enough to distinguish step of 5 nm. Depicted interference and phase pictures illustrate the possibility to

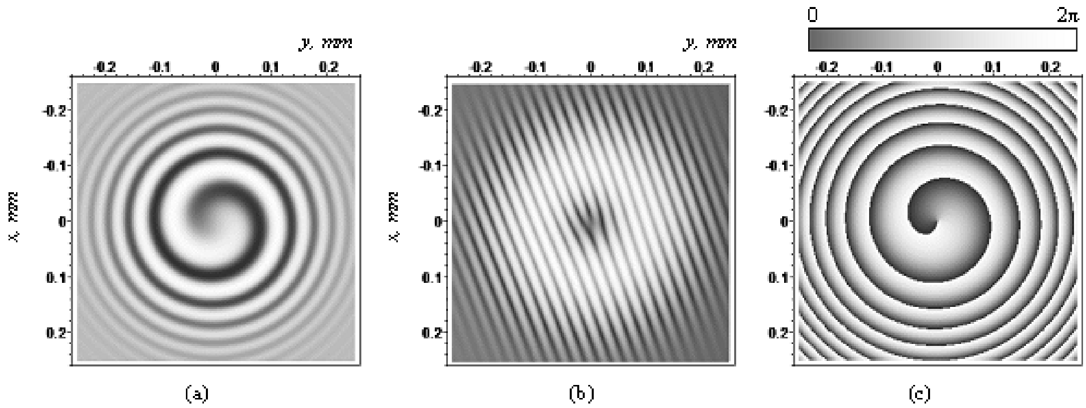

Figure 1: Calculated interference pattern of singular beam in axial (a) and tilted beams (b) and its phase pattern (c) with topological charge $\xi = +1$. Beam parameters are next: $\omega_o = 70\ mcm$, $n_x = 1.54$, $z = 20\,mm$, $\lambda = 632.8\ nm$.

process not only clear phase of singular beam, but also directly the spiral produced by interference of singular and Gaussian beams after some adjustment of contrast and brightness. This method is applicable for fast and rough analysis of sample's shape.

3. Results and discussion

Due to the high sensitivity of singular beam phase to the small distortions of the wavefront, the interference of the reference beam and the Laguerre-Gaussian beam transmitted through the isotropic thin plate coated with a wedge-shaped layer of 500 nm thickness makes possible to analyse the rotation of the spiral phase, depending on the thickness of the applied layer, as well as a surface topology in reflected beam regime.

In case when singular beam propagates through the isotropic plate with a stepped profile so that the reference (zero-order) plane coincides with the lower edge of the surface, whereas due to the optical path difference from lower to height surfaces we can observe a phase shift (see Figure 2(a). This effect may serve as a basis for high-resolution microscopy devices. In contradistinction to classical methods which uses plane wave, the singular beam with helical wavefront has a unique feature – the spiral interference pattern and its rotation can be easy recovered with computer processing in real-time.

To enable rapid implementation and universal phase recovery method of vortex beam with images from the CCD camera, we used the method proposed in the works [17, 21–23]. For the comparison of object beam with the reference one the Mach-Zehnder interferometer was used (see Figure 2 (b). The sharp thick fringes with a characteristic "fork", corresponding to optical vortices were imaged by the camera and assayed. For draft regime of surface analysis was used only interference spiral without any additional computing. Total phase shift which is observable due to angular rotation of interference spiral can be calculated from simple equations: $2\pi \sim \lambda$, $\Delta\phi \sim n(d_1 - d_2) = nh$, where $d_1 - d_2$ is a difference between observable and neighboring levels of sample surface (geometrical path), nh– optical path difference and $\Delta\phi$ – phase difference caused by various. Overall depth map can be compiled with step by step scanning by XY translation table, thus whole probe may be scanned.

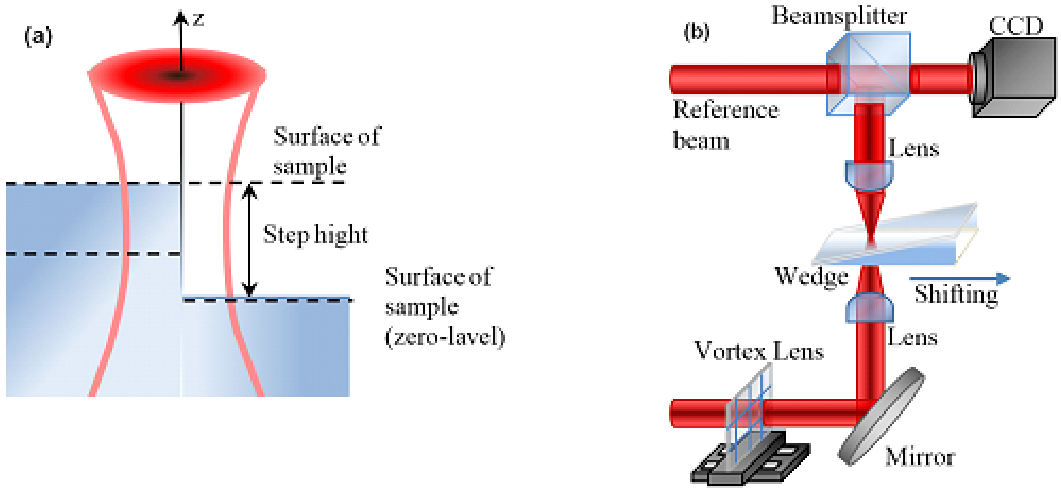

Figure 2: Singular beam spreading through the phase step (a); Part of experimental set-up based on Mach-Zehnder interferometer (b).

Evaluation of phase sensitivity shows that the distinguishable spiral phase rotation occurs at the isotropic plate thicknesses equals to $\lambda/120$, where λ – is a wavelength. The overall resolution of vortex microscope based on phase-shifted singular beam is determined by shift-retrievement algorithm and may exceed diffraction limits for lens systems.

4. Summary

In the present research we have theoretically and experimentally considered evaluation of singular beam's phase sensitivity and have shown that the distinguishable spiral phase rotation occurs at the isotropic plate thicknesses equals to $\lambda/120$, where λ – is a wavelength. Proposed technique may be applied to microscopy of optically transparent and reflecting surfaces with exceeding optical diffraction limit. Moreover, this method is applicable for non-destructive testing of live cells and biological tissues in real-time regime. Automatic processing of vortex spiral interferograms in conjunction with focusing unit will allow to achieve theoretically calculated limit of vertical resolution down to 1,75 nm for visible light and longitudinal resolution down to 7 nm.

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