Determination of microrelief of the sample by singular beams superposition

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Abstract

In present paper we propose easy way to implement method of interfering vortices with opposite topological charge for the real time determination of the thickness and information about the surface of studied samples with the resolution up to 7 nanometers. The determination of the characteristics of the medial cross-section of submicron-objects becomes possible due to phase sensitivity of interfering singular beams to the slightest changes in the optical path difference between them. The dependence of rotational angle of resulting interference pattern in case of different sample thickness for two singular beams superposition is considered in detail.

Keywords: optical vortex, phase, optical microscopy, singular beams, surface relief detection.

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Introduction

Intensive developing of nanotechnologies in electronics, engineering, biology and biomedicine needs new techniques for fast, low-error and easy in realization measurements and increasing the resolution of existing methods of optical microscopy. Thus, in order to meet the new needs of applied sciences a large number of recent publications in the field of modern optics were devoted to the problem of beam reflection or its propagation through the studied samples for both: coherent and non – coherent light sources [1 – 3] in order to develop methods for non-contact study of micro- and nanostructures in material processing as well as biomedical applications [4].

One of the most common principles of optical microscopy – scanning probe microscopy, is an area of microscopy in which the image of the object surface formed by a probe scanning its surface. The image obtained by mechanically moving the probe along a path in the form of a raster (line by line) and registering the interaction between the probe and the surface as a function of its position. This type of microscopy includes Scanning Near-field Optical Microscopy (SNOM), Atomic Force Microscopy (AFM), and Scanning Tunneling Microscopy (STM) and wide range of Fluorescence Microscopy modifications [5 – 8].

Furthermore, Stimulated Emission Depletion Microscopy (STED), a type of fluorescence microscopy that achieves a resolution in excess of the diffraction limit by selective fluorescence quenching, can be distinguished [9]. An important advantage of STED microscopy is that the resolution improvement achieved in real time and usually does not require long-term data processing. Also, a newest application of “doughnut” beam carrying tightly focused optical vortex by high numerically aperture objective was implemented in STED microscopy [4, 8 – 11].

Another method named Optical Vortex Scanning Microscope for visualization and analysis of nanometer structures, where the sample is scanned by a moving vortex, was demonstrated in work [12]. Hence, the way of investigations the surface roughness and the thickness of the sample were demonstrated in work [21] by analyzing interference patterns in the form of a vortex spiral. The interference patterns between reference beam and object vortex beam passing through the sample demonstrates rotation depending on surface parameters of the sample. In contrast to [17 – 19] probe beam contain single charged optical vortex which interfered with Gaussian beam and rotation of interference pattern analogous to “two-lobed
fields” allow to define surface height difference by angular orientation. The method has shown good results due to the high sensitivity of singular beam phase to the small distortions of the wave front caused be the sample. However, one of the significant drawbacks should be indicated as the complexity of the determination the rotation of the interference spiral with sufficient accuracy.

In this paper, we propose an optical scheme of investigation of the sample profile with nanoscale resolution based on the analysis of evolution of the interference pattern of two superimposed vortices with single topological charges and opposite signs. This method is suitable for the real time determination of the thickness and information of surface of studied samples. The determination of the characteristics of the medial cross-section of sub-micron-objects becomes possible due to phase sensitivity of the singular beam to the slightest changes in the wave field. The dependence of the angle of rotation of the resulting interference pattern of two singular beams on the sample thickness is considered in detail.

1. Theoretical basis

The phase and propagation characteristics of Laguerre–Gaussian (LG) beam are of great current research interest in relation to the practical application of the LG beams, in particular, in microscopy. A large number of publications in recent years are devoted to the problem of beam reflection or its propagation through the studied samples for coherent and non-coherent light sources in order to develop metrological methods for non-contact study of nanostructures. These principles can be used for investigation the surface profile of samples of different nature with high resolution [11–18]. Summarizing, Laguerre–Gaussian beams carrying low-order optical vortex is the most convenient as a probe beam for determination of microrelief of the sample. The method has shown good results due to phase sensitivity, separated by a thin dark band corresponding to the minimum intensity.

Computer models of the transverse intensity and phase distributions in the singular beams, as well as the result of their interference, are presented in Fig. 1.

Phase images can be considered as a two-dimensional phase distribution or as an optical path difference of interfering rays. For visualization of optically inhomogeneous transparent media, it is known that the dependence of the optical path difference is proportional to the local projection of the refractive index on the beam direction:

\[ h(x,y) = \frac{\lambda \phi(x,y)}{4\pi n(x,y,z)} \]

where \( \lambda \) – the wavelength of the incident wave.

The main task is to analyze the dynamics of the recorded intensity when the phase difference of the interacting beams changes. When the optical paths of two beams in the arms of the interferometer are close, the interfering waves have the same radius of the beam waist \( \omega_0 \) and the curvature of the wave front. Only in this case we may obtain symmetrical intensity distribution of superposed singular beams.

The method of determining the angle of rotation for the interference pattern is quite simple. The program determines the center of the dark band between two slices of maximum intensity, through which a line is drawn as shown in Fig. 2, with respect to which the rotation of the similarly constructed line of the following interference pattern is determined when the optical path difference of the interfering beams changes, corresponding to the elevation of the sample.

Thus, the analysis of the changes in the obtained interference patterns allows us to extract information about the phase shift between the superimposed beams and the state

\[ z_R = \frac{k\omega_0^2}{2} \]

where \( z_R \) determines the Rayleigh length, \( \omega_0 \) – beam waist in the plane of incidence on the surface of the sample \( z=0 \), \( l = \pm 1 \) – topological index, \( w = \omega_0 \sqrt{1 + (z/z_R)^2} \) – current beam waist, \( \varphi = \arg(x + iy) \) – azimuthal angle, \( r = \sqrt{x^2 + y^2} \), \( k = n \cdot (2\pi/\lambda) \) – wave number in the medium with refractive index \( n \).
of surface roughness and thickness of the sample, as well as the problem of optimizing such procedures in practice.

In practice, it is possible to use two types of measurement schemes: when the singular beam is a probing beam and when the vortex is introduced into the reference beam. In both cases, the interference patterns are the same, but the direction of their rotation will be inverted.

Fig. 1. Numerical model of LG beams superposition with opposite topological signs: (a) intensity distribution (inverted) of LG beam with unit positive topological charge and opposite one (b) respectively; (c) and (d) – the pairs of phase maps correspond to the phase patterns of optical vortices (LG beams with zero radial index) and opposite topological charges; (e) is the resulting pattern of superposition of two LG beams of equal and opposite by the sign topological charges and (f) corresponds to the phase portrait of interfered singular beams.

Parameters of superimposed beams were the following: \( \omega_0 = 180 \ \mu m, n = 1.00, z = 1 \ m, \lambda = 632.8 \ \text{nm} \)

2. Phase-shift retrievals for transparent threads: an experiment

Due to its high sensitivity to wave front inhomogeneity, caused by geometry of the sample, optical vortices and their interference was adopted to surface roughness analysis and curvature imaging of reflecting surfaces [2, 21]. Nevertheless, transparent samples with complex relief of boundary surface may have an inhomogeneity of refractivity index. Both these parameters define the overall optical path difference between object and reference beams. From this point of view, such samples are amplitude-phase objects. The simplest way for fast and computationally-non-intensive analysis of such objects should be used in form of direct data acquisition from image sensors and cameras with minimal adjustments and transformations. For this purpose, a superposition of a high-sensitivity probe beam carrying optical vortex with a reference beam also containing a singularity with the opposite sign was used. To estimate the sensitivity of two-singular beams interference method we restrict ourselves on consideration only homogeneous isotropic media as, for example, thin cover slip. Typical cover slip has 250 \( \mu m \) thickness and high quality of parallelism. In case, when the singular beam slide on the isotropic plate with a gradient surface profile, we can choose an arbitrary position and set it as starting point, thus all the next measurements will be written relatively to the value of phase-shift at this point in terms of angular turn of intensity pattern. This effect becomes the basis for a high-resolution microscope device, where rotational process may be easily captured experimentally and processed automatically in real time.

Typical experimental set-up for two-beam interference includes vortex beam shaping unit and interferometer with almost equal distances in object and reference arms to avoid beam waists misalignment. The scheme, proposed in Fig. 3c, allow to control test object position and very optical path difference between the beams. The light beam from the He-Ne laser is converted into the single-charged vortex beam by computer generated hologram H with “fork”-shape amplitude produced by photographic method [35–37]. The first diffraction order was cut by the diaphragm D and five-times expanded with telescope T. Next the telescope T beam splitter BS1 splits the initial vortex beam with topological charge \( l = +1 \) to the object and reference beams, the reference beam has opposite sign of charge \( l = -1 \) for receiving of appropriate interference pattern on the CCD camera. Microscope objectives MO1 and MO2 10x with numerical aperture 0,30 focused the beam on the sample surface and project the
light on camera matrix. Both microscope objectives adjusted so that to receive parallel light beam after the sample without scale transformation. Taking into account that polarization state has greatest influence to the longitudinal component of the electric vector of the light field, thus the greatest visual difference in the intensity picture is observed when using the first-order vortex, which was demonstrated in [38, 39].

Slightly inclined test sample makes possible to control the effective optical thickness, which causes on phase shift between the beams. This process is observed visually by turn of interference pattern, as shown in Fig. 4. Stabilization of interference pattern was reached by synchronization of probe beam and reference one with the sample itself. Such principle allow avoiding instability of interference pattern caused by random movement and shudder. Moreover, proposed method is resistible against the aberrations of optical elements since only central part of the beam carrying necessary information about vortex phase.

Fig. 4 shows the dynamics of interference pattern for different values of optical path difference. The intensity minima correspond to unfolded phase profile of superimposed beam and may be easily recognized with computer vision procedures. The geometrical thickness of the sample under test is defined as optical path difference divided by refractivity index \( n \) of glass, where \( n = 1.5168 \).

Fig. 4. The evolution of superposition of vortex beams with opposite signs of topological charge for different optical path differences \( z + \delta \). (a) Experimental patterns (inverted) and (b) corresponds to computer simulation of intensity distribution (inverted), (c) shows the evolution the phase of resulting field \( \Im E(r, \varphi) \).

An estimation of sensitivity for turn of superposition pattern indicates that the resolvable threshold for determining the rotation angle of the pattern is \( 3^{\circ} \) for current state of the experimental set-up. One full turn occur, when optical path difference acquires the value of a multiple of the wavelength \( \lambda \), for He-Ne laser (\( \lambda = 632.8 \text{ nm} \)) the vertical resolution is \( \delta = 10.54 \text{ nm} \). In dependence of media refractivity index \( n \neq 1 \), the total resolution for
physical thickness measurement may be expressed as \( \delta_{\text{geom}} = 10.54/n \) and reaches for glass material (BK-7) with \( n = 1.5168 \) \( \delta_{\text{geom}} = 6.95 \) nm.

The total phase shift observed by the angular rotation of the interference spiral was calculated using simple expressions:

\[
\delta \varphi = 0 + 2\pi, \quad m\lambda = n(d_1 - d_2) = nh, \quad \text{where} \quad d_1 - d_2 = \text{the height difference between two adjacent levels of the sample surface (geometric path),} \quad m\lambda = \text{the optical path difference with multiply factor} \quad m \quad \text{and} \quad \delta \varphi = \text{is the phase-shift caused by difference in thickness. A complete depth map can be compiled by step-by-step scanning in the } xy \text{ plane by the sample holder transverse movement, so that a sample may be examined and imaged without limitations to linear dimensions.}
\]

**Conclusion**

Development of new methods for phase shift analysis in application to thickness measurement is the quite important issue in fundamental and applied research in optical noninvasive metrology. A great attention paid to the development of optical methods is caused, first of all, by the fact that in field of applicable measurement technics in nano-research and the nano-systems industry is not limited from the point of view of image quality improving, but also has great importance for such tasks as recording information in the optical environment, lithography, nano-structuring and optical manipulation. In particular, great attention was attracted by the possibility of using interferometric methods for investigating stepped structures in industry and, as a result, may be applied to interdisciplinary research as biophotonics and medicine.

This research presents the results of theoretical analysis, simulation and experiment, the sensitivity of singular beams to external perturbations is determined. It is shown that a discernable rotation of intensity profile arises during the changes of sample thickness with step of 6.95 nm. The proposed technology is used in the microscopy of optically transparent and reflective media, where the method benefits from the undemanding to optical elements quality and distances between them in the experimental setup. This approach enable to scale it for successfully deploying in the measurements of stepped structures as thin films, coatings and roughness of substrates in noncontact operation regime, as well as in area of biophotonics and crystal optics. Thus, proposed imaging method is performed non-invasively on intact, fully functioning organisms, real time microscopy allows the study of development in evolution.

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