

Abstract of doctoral dissertation

“Optical properties and development of flat-surface nanostructured gradient index micro-optical vortex phase components”

The dissertation discusses new prospects for tailoring the properties of optical beams. Specifically, its intensity profile and the phase structure can be modified using developed, flat-surface nanostructured gradient index (nGRIN) micro-components. Both surfaces of the nGRIN micro-components are flat and this unique property enabled novel functionalities of such a phase element.

The thesis mainly focuses on nanostructured Vortex Phase Masks (nVPM), which are designed with the use of effective medium theory and simulated annealing approximation method. Cost-effective modified stack-and-draw nanostructurization was used in the fabrication process. In contrast to Spiral Phase Plates, nVPMs rely only on the internal refractive index gradient, and thereby there is no need for spiral relief on its surfaces. This makes its optical performance not affected by different surrounding media. The mask can be immersed in air, water, ethanol or any other transparent liquids and resulting vortex beam will have the same value of the topological charge. In addition, the dissertation aims at novel fiber-based devices such as fiber-vortex microprobe converters. Furthermore, the design of its improved achromatic version for generation of white-vortex beams was proposed. The vortex fiber probe has high application potential in optical trapping and particle manipulation as well as in laser micromachining. The flat-surface nVPM element can be used as a component of an all-fiber laser vortex beam generator, which can be integrated with an fiber laser resonator. The fiber vortex generator is a compact and reliable device compatible with the fiber technology.

The first part of the dissertation is devoted to the theoretical study on nGRIN VPMs in order to improve the optical quality of the generated optical vortex beam. There is a need for optimization because GRIN VPMs suffer from the light wave-guiding effect leading to the azimuthally non-uniform light intensity distribution in the resulted vortex beam. The effect is a consequence of the azimuthal refractive index profile of the mask. In the profile, there is one area along the radius of abrupt refractive index change, and light tends to concentrate in the highest refractive index area of the mask. The influence of the refractive index contrast of component glasses, effective refractive profile distribution of the masks on the intensity distribution, and phase structures of the generated vortices are studied. Numerical simulations employing Fourier Transform-based Beam Propagation Method were used to validate potential methods of improving the intensity profile of the vortex beam. Eventually, we proved that the best approach so far in this matter is using two types of glass with a large refractive index difference which allows the fabricated mask to be very thin. Lesser thickness minimizes the effect of light waveguiding in the nVPM mask. Research done in scope of the thesis showed that the further improvement can be obtained by making azimuthal gradient of refractive index of the GRIN mask described by power functions. Furthermore, it is possible to utilize the nanostructured phase mask to generate the vortex beam with relatively high topological charges.

The second part of the dissertation focuses on optical experiments performed to evaluate the quality of the generated vortex beams by means of developed nGRIN VPMs. The sample-set consists of our in-house developed nVPMs with different mask thicknesses. The optical performance of one of the selected nVPMs was evaluated in different transparent media air, water, and ethanol to show nVPM's advantage over SPP. We used two experimental techniques to

measure topological phase characteristics of the generated vortex beam: the astigmatic transformation and Mach-Zehnder interferometry. Through comprehensive theoretical analysis and experiments, we proved the robustness of the nVPMs in optical vortex generation vortex beams up to topological charge two. The main advantage of this kind of the phase element (optical performance preservation in any transparent external media) is explained with appropriate theory.

The next part of the dissertation describes the development and characterization of a novel fiber-based microprobe consisting of a 28- μm thick nGRIN VPM integrated at the end of an optical fiber. Specifically, regular single-mode optical fiber operating at the wavelength of 633 nm was used. The additional coreless fiber was designed and assembled with the probe to expand the beam on the mask's surface. Experimental and theoretical studies proved that the probe efficiently converts fiber-guided fundamental mode into the optical vortex beam with a single topological charge. It is worth mentioning, the optical performance of the complete vortex-fiber probe was not affected by immersion in air, water, or any uniform, transparent media. This is not possible for other already reported fiber-based systems, which use conventional SPP relief. The research results also confirm the compatibility of the proposed nanostructurization method with fiber technology, which gives high application potential. In particular, the probe could substantially simplify and improve the reliability of optical set-ups used for optical trapping or particle manipulation. Moreover, fiber-based vortex probe could be beneficial in future vortex beam applications in optical telecommunication. Due to the high laser damage threshold of the mask's materials, the probe's all-glass structure makes it a perfect candidate for vortex beam converter for laser micromachining applications.

Finally, another essential improvement of nGRIN VPMs is presented. The nVPM was redesigned in order to gain achromatic properties. The improved mask aims at white-vortex beams, which is a very vibrant subject in the field of singular optics. It enables generation of optical vortices at multiple wavelengths, all having the exact topological charges. This is achieved by carefully selecting the glass pair to fabricate the mask, those having proper refractive index dispersion curves. It was motivated by the experience of our research team in developing nGRIN microlenses with minimized axial chromatic aberrations. Besides proper refractive index difference profile of glass materials, it has to meet other nVPM fabrication constraints. Furthermore, the designed and optimized white vortex binary mask structure has been prepared for the fiber drawing process.