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Direct electron-beam writing of continuous spiral phase plates in negative resist with high power efficiency for optical manipulation

Photonics Research Centre, School of Electrical & Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798, Singapore
K. Dholakia
School of Physics and Astronomy, University of St Andrews, Fife, Scotland KY16 9SS
H. Wang
Microelectronics Division, School of Electrical & Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798, Singapore

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Laser beams propagating in Laguerre-Gaussian (LG) modes are of considerable interest due to their widespread applications in the areas of optical manipulation of microparticles, quantum entanglement of photons, nonlinear optics, optical vortex interactions, and atomic studies. However, the proliferation of LG beams has been hampered due to the absence of reliable and reproducible fabrication technologies in producing the required optical elements for their generation. In this letter, we describe a simple, reliable, and reproducible fabrication technique for a micron-sized spiral phase plate with high power efficiency (80%–90%) and good beam uniformity. This facilitates the widespread use of LG beams in various applications; as an example the fabricated elements can easily and readily be incorporated into an existing optical trapping system with minimum modification. © 2004 American Institute of Physics. [DOI: 10.1063/1.1830678]

Optical vortices have been widely used in the field of singular optics,1 optical traps,2 quantum entanglement,3 and nonlinear optics.4 At present, computer generated holograms (CGHs) have been frequently employed to create Laguerre-Gaussian (LG) beams, to be used as optical traps or the study of vortex interaction hosted in a coherent source. When the hologram is displayed onto spatial-light-modulators (SLMs), the LG beams can easily be reconstructed with an arbitrary topological charge. However, even though such a technique allows a straightforward means of the LG beams, it is impeded by high cost, moderate power efficiency, and deficient resolution of the SLMs as well as the diffractive nature of holograms. Other means to obtain a high efficiency LG beam are the use of cylindrical lens mode converters, static blazed computer generated holograms, or spiral phase plates (SPPs). These less-dynamic alternative techniques often offer a higher efficiency than the SLM approach of generating higher mode LG beams. However, they do have their shortcomings. The cylindrical lens mode converter requires the laser output to be a higher order Hermite-Gaussian (HG) transverse mode. Static blazed computer generated holograms though have the ability to take higher power, but require advanced computational algorithms and effort in alignment. The SPP, however, offers a direct method that allows a direct conversion of Gaussian beam to a LG beam without changing beam’s propagation direction or requiring an HG laser source. Furthermore, the SPP being made of glass material is able to take high power laser illumination with low failure rate. We show the ability to easily generate LG modes with high efficiency using SPP. In contrast to previous studies,5,6 the technique of SPP generation presented here is simple, reproducible, and reliable. In addition the SPPs are in the micro size region allowing for more compact setups for optical traps for example.

There are several techniques in the fabrication and characterization of SPPs. In the recent work by Oemrawsingh et al.,5 a high quality circular SPP has been fabricated and characterized. In that work, a high quality SPP capable of generating optical vortices of a low specified charge at visible wavelength was fabricated by micro-machining and molding techniques. This reported technique allows the production of high-quality smooth circular SPP having a maximum height of about ~4 μm and a diameter of ~4 mm. However, such an optical phase plate is still within the millimeter regime. Hence this could be a problem if we are to integrate the SPP into any existing micro-optical beam shaping systems for trapping.

Here we report a simple and highly reproducible fabrication technique for high efficiency micron-sized circular SPP using electron-beam lithography (EBL). The efficiency and beam profile of the resulting LG beam generated from the SPP is measured, using a power meter and a commercial beam profiler. We show via an interference experiment the presence of the vortex within the LG beam. Finally, we also show that the micron-sized SPP can easily be incorporated into any optical trapping setup for optical manipulation and use the aforementioned plates for creating circular arrays of optically trapped spheres.

The SPP, based on the mathematical function of $e^{i\lambda l}$ (l integer), has basically a continuous and spiral profiled surface. The spiral surface forms one period of a helical wavefront, with an associated step discontinuity. Upon transmission through the SPP, a beam of wavelength (λ) is subjected to a phase delay that is proportional to the azimuthal angle (θ). This phase delay would result in an intensity pattern comparable to the LG beam. By inserting the phase element...
along the propagation axis of the Gaussian beam, the equation of the radial electric field is proportional to the product of a Gaussian and an associated Laguerre polynomial \( L_0^l \). In the case when \( l \) is greater than zero—in our case \( l = 1 \)—the electric field has an azimuthal phase change of \( 2\pi l \), which results in a phase singularity in the field and a node in the intensity at the center of the beam. It has been shown that the LG beam possesses a well-defined orbital angular momentum linked with inclined wave fronts as a consequence of the azimuthal phase term.

In our previous work, we have demonstrated the lithographic technique for continuous surface relief structures using negative resist such as the commercial negative resist (SU-8) and the titanium-based hybrid sol-gel glass using the direct EBL technique.

For this work, the SPP was fabricated in negative resist (SU-8) using LEO982 FESEM converted lithographical tool with the ELPHY Quantum EBL system. The diluted resist was first spun-on an indium-tin-oxide coated glass at 2000 rpm for 1 min. Next the spun sample is sequentially soft-baked on a hotplate at 65 and 90°C for 1 min. In this work, the exposure will be carried-out using an accelerating voltage of 25 keV and beam current of 100 pA. A calibration of resist thicknesses versus exposure dosages for the formation of grey-scale continuous self-relief structure was carried out. After development, the dependence of the resist film thickness on the e-beam exposure was measured as shown in Fig. 1. The resist film demonstrates a high sensitivity of \( 3.5 \) \( \mu \)C/cm\(^2\) and a low contrast of \( 1.1 \). Having a low resist contrast, in this case, is a very important property for fabrication of multilevel and continuous surface relief structures where grey-scale exposure as a reasonably big variation of exposure dosage would effect controllable and relatively small variation of the resultant structure height. Using resist thickness and energy dosage characterization data obtained earlier, the required energy dosages for a 24-level circular SPP can therefore be extracted easily. The exposed samples were developed in developer for 30 s with mild agitation and rinsed immediately in de-ionized water for 1 min before gently blown dried by \( N_2 \).

The surface topology of the fabricated circular SPP (500 \( \mu \)m in diameter), whereby the element has an actual height of \( \sim 1.04 \) \( \mu \)m was inspected under a scanning electron microscopy and a Deteck\(^3\) Surface Profiler as illustrated in Figs. 2(a) and 2(b), respectively.

We generated several SPPs for topological charge \( l = 1 \). The measured efficiency of mode conversion, using a commercial power meter, from the SPP varied from 80% to 87% for various plates we fabricated. Subsequently, a detailed beam profile of the LG beam is measured as shown in Figs. 3(a) and 3(b). The horizontal intensity and vertical intensity profile are shown to have a peak difference of approximately 10% and approximately 5%, respectively. The LG beam generated by the SPP has an annular intensity beam distribution that is azimuthally uniform to 10%.

Subsequently, the LG beam generated using the SPP was directed into a Michelson interferometer\(^10\) to observe the topological charge of the LG beam as shown in Fig. 4. The interference pattern showed two-single but opposite charged dislocations formed by the interference of two LG beams of the same helicity. By interfering the opposite (but equal in magnitude) helicity of the optical vortices, we are able to reduce the Gouy phase mismatch and clearly observe the optical vortices phase dislocations.

To test the SPP in an appropriate application, we incorporated the fabricated phase element into our upright optical trapping setup using a Carl Zeiss Axiostar Plus microscope. The SPP was mounted onto a rotating \( x-y-z \) stage, in the propagation path of a 30 mW linearly polarized HeNe laser with a wavelength of 632.8 nm. The generated LG beam was directed through the 100\( \times \) objective at a sample containing micro-spheres dispersed in water, with around 25 mW of power at the sample plane.
One of the key advantages of the micron-sized spiral phase plate is the ability to modify the optical beam from a Gaussian beam into a LG beam without changing the footprint size or alignment of the apparatus. The SPP was placed at the midway between the two conjugate lenses and thus could be removed without introducing any misalignment in beam path within the apparatus. This is in contrast to using a CGH or mode converter for LG beam generation which would require beam adjustment of the trapping apparatus. This feature of our system allows insertion/removal of the SPP in a simple fashion, making it amenable to a non-optics end-user (e.g., biologists), as shown in Fig. 5.

In Figs. 6(a) and 6(b), we showed trapping of five silica spheres with the same diameter of 3 μm, where n is the refractive index. We noted that the available power was low and a rotation due to scattering of light from the inclined wave fronts of the LG beam was observed at a slow rate of ~0.3 Hz.

In conclusion, we have been able to experimentally demonstrate a simple, reliable, and reproducible technique for the fabrication of highly efficient micron-sized SPPs. The efficiency of the fabricated SPP has been verified using various means, such as power meter measurement, beam profile measurement, optical manipulation of microparticles, and interference experiment. Having such a high efficiency and yet economical spiral phase element will facilitate the proliferation of the use of SPPs in various applications such as optical traps for micromanipulation, atomic physics studies, and quantum information processing. In addition, given the flexibility of this fabrication technique, these SPPs can easily and readily be incorporated into an existing optical trapping system with minimum modification.

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FIG. 5. Optical trapping setup of a 30 mW linearly polarized HeNe laser with a low Gaussian beam divergence angle is collimated into the 100× microscope objective of n.a. 1.25 for trapping using the telescopic arrangement using lenses L1 and L2. The SPP, of 500 μm in diameter, is inserted in between the pair of lenses L1 and L2.

FIG. 6. (a) Five silica micro-spheres 3 μm (each) with n=1.49 (left). (b) Six latex micro-spheres 3 μm (each) with n=1.59 (right). Micro-spheres are trapped at the annular intensity rings of the LG beam using the fabricated SPP.