Triple-Helix Tractor Beam Generation with a Dielectric Metasurface Pancharatnam-Berry Phase Hologram

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Abstract: We present a silicon-based Pancharatnam-Berry (PB) phase metasurface hologram that produces a triple-helix solenoid tractor beam from a Gaussian input beam. Our metasurface has a >90% diffraction efficiency and >75% transmission. © 2020 The Authors

1. Introduction

Recent developments in optical manipulation have included the emergence of optical tractor beams based upon a class of non-diffracting beams known as solenoid beams. These translationally quasi-invariant beams have been shown to exert long-range and retrograde (toward the source) optical trapping forces [1]. These beams are prepared via a coaxial superposition of Bessel beams of different order. Thus far, solenoid beams have been realized with optical systems that use spatial light modulator (SLMs) to convert Gaussian laser beams into helical beams carrying orbital angular momentum (OAM). The SLMs add the required phase profile to the wavefront [2]. SLM-based systems have been used to generate solenoid beams with efficiencies as high as 30%. Further improvements to efficiency are limited by the micron-scale resolution of current SLMs, their discretized phase levels and the need for other bulk optical elements such as lenses. Here we present a method that overcomes these efficiency constraints. We design and fabricate an amorphous silicon PB phase metasurface hologram. We show that it produces a triple-helix solenoid beam from a right circularly polarized (RCP) Gaussian input beam at a wavelength of $\lambda=1064$ nm.

2. Results and Discussion

Fig. 1. (a) Schematic of single α -Si nanopillar, from which metasurface hologram is comprised. (b) Phase profile required for triple-helix solenoid beam with a 9° deflection angle. (c) Optical micrograph of fabricated metasurface (scalebar: $25\ \mu\text{m}$). Inset: zoom-in of center of hologram in (b).

The solenoid beam hologram is comprised of amorphous silicon nanopillars on a borosilicate glass substrate (Fig. 1a). Each nanopillar has height $H=505$ nm, length $L=305$ nm, and width $W=130$ nm. These are arranged in a square array (period $\Lambda=430$ nm) to form the metasurface, whose overall extent is $2.5\ \text{mm} \times 2.5\ \text{mm}$. Each nanopillar is designed to act as a half-wave plate with its fast-axis oriented at an angle θ . RCP light passing through the metasurface will be converted to left-CP light and also accumulate a PB (or ‘geometric’) phase shift of $\phi=2\theta$. The required phase distribution to convert a collimated Gaussian beam into a triple-helix solenoid beam is shown in Fig. 1b. This in turn determines the orientation angles of the pillars in the metasurface. The triple-helix solenoid beam is

equivalent to two superposed OAM carrying Bessel beams with OAM -10 and -7 and internal angles 0.005 and 0.004 respectively [3]. The nanopillars are formed using e- beam lithography and reactive ion etching, using a Cr etch mask (30 nm thick). Fig. 1c shows an optical micrograph (with crossed polarizers) of the center of the fabricated metasurface hologram. This fabricated structure is in good agreement with the design (inset Fig. 1c).

By illuminating the metasurface hologram with an RCP Gaussian laser beam ($\lambda=1064$ nm, beam width ~ 3 mm, TEEM Photonics), a triple-helix non-diffracting beam is generated along the direction corresponding to the $+1^{\text{st}}$ diffraction order. We measure the transmission through the hologram to be $\sim 76\%$ with diffraction efficiencies of ($\sim 1\%$, $\sim 6\%$, $\sim 93\%$) for the $(-1^{\text{st}}, 0, +1)$ orders. Hence, $\sim 70\%$ of the total input laser power is diverted into the desired beam, with $\sim 24\%$ lost to reflections, scattering and absorption and $\sim 5\%$ carried by the other two diffraction orders.

Our metasurface hologram converts the Gaussian input beam (~ 3 mm wide) into a solenoid beam (~ 1 mm wide). Figs. 2 a-d show the beam profile at four locations along the optical axis (at up to 17.3 cm from metasurface). The non-diffracting nature (critical for long-range tractor beam operation) is clearly seen, as the solenoid beam diverges by only 0.015° over the 9.8 cm distance over which the measurements are made. A rotation of 90.76° of the three intensity maxima about the propagation axis can also be seen over this distance, demonstrating the helical nature of the beam. The beam divergence and rotation are found via the MATLAB tool “cpselect” and the MATLAB function “fitgeotrans”. Our triple-helix beam would thus complete one revolution after 38.87 cm of propagation.

Fig. 2. Imaged transverse beam profiles of the generated non-diffracting solenoid beam (a) 7.5 cm, (b) 10.7 cm, (c) 14 cm and (d) 17.3 cm from the metasurface hologram.

3. Conclusion

We have designed and fabricated a silicon PB phase metasurface hologram that generates a triple helix solenoid beam from a circularly polarized Gaussian laser beam input (at $\lambda=1064$ nm). We recorded an overall conversion efficiency of $\sim 70\%$ and a diffraction efficiency of $\sim 93\%$. These figures greatly outperform previous approaches that rely upon conventional optics such as SLMs and lenses. Solenoid beams have been shown to exert optical pulling forces on microscopic objects over large distances, making them of interest in various fields including optical tweezing and manipulation as well as celestial sample collection.

4. Acknowledgements

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5. References

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