Generating Optical Vortex Needle Beams with a Flat Diffractive Lens

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Focused optical vortices (FOVs) offer rich potential for both fundamental research and practical applications. These applications span from manipulating the photonic spin Hall effect to enhancing optical communications, trapping and manipulation, microscopy, and high-resolution imaging[1]. A critical factor in these technologies is axial resolution, driving the demand for FOVs with extended depth-of-focus (DOF).

In our project, we designed, fabricated, and tested a flat multi-level diffractive lens (MDL) to extend the DOF of a standard optical vortex, resulting in an optical vortex needle beam (OVNB). The MDL achieves dual objectives: it focuses an input optical vortex at a desired working distance while significantly extending the DOF beyond that of a conventional lens[1]. Our MDL design, generated using inverse design techniques, was then fabricated via grayscale-optical lithography.

To validate the MDL's effectiveness in extending FOV depth of focus, we conducted experiments with the setup shown in Fig. 1 (a). We illuminated the MDL, an image of which is shown in Fig. 1 (c) and its phase distribution shown in Fig. 1 (d), with an optical vortex and measured the resulting point-spread function (PSF) over varying distances. Our optical setup involved applying a hologram, shown in Fig. 1 (b) to a spatial light modulator (SLM), which modulated the amplitude and phase of an incident Gaussian beam. After propagation, the optical vortex formed in different diffractive orders[1]. We isolated the first-order optical vortex using a spatial filter placed between lenses L_3 and L_4, allowing it to pass through the MDL. Additionally, we observed the formation of the OVNB and the interference between the FOV and the Gaussian beam, shown in Fig. 1 (g), confirming the value of $l = 1$ for the FOV[1].

Our experimental results, as shown in Fig. 2 (a-f), demonstrate that the FOV's beam size remains relatively stable over the propagation distance with the MDL, while it monotonically increases as a function of distance without the MDL. These findings align well with our simulations. We also measured the efficiency and intensities of the PSF at different l values, as shown in Fig. 2 (g-h). Looking ahead, we plan to explore the generation of non-diffractive FOVs with smaller beam sizes across a broad spectral range.

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[1]Anita Kumari, Vasu Dev, Tina M. Hayward, Rajesh Menon, and Vishwa Pal. "Generating optical vortex needle beams with a flat diffractive lens." *Journal of Applied Physics,* 136(11), 113105 (2024). DOI: 10.1063/5.0226316 .

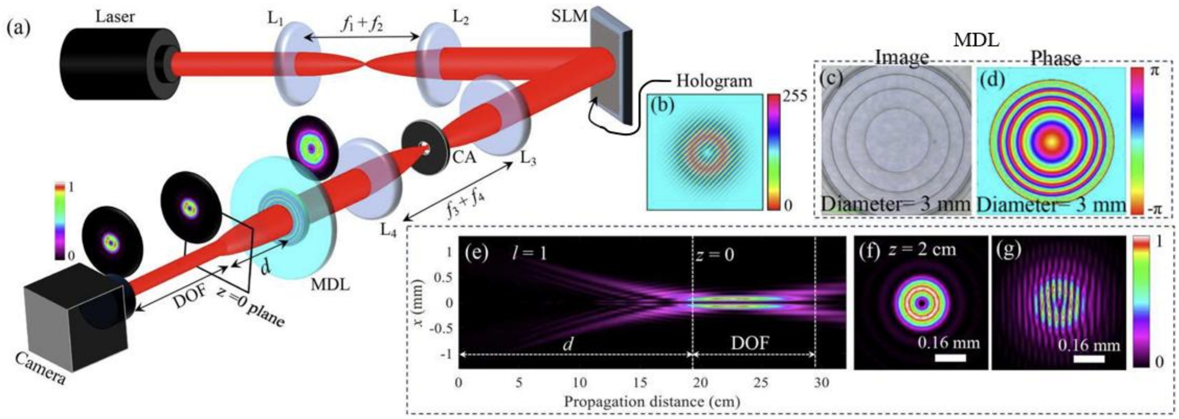

Figure 1: (a) Experimental arrangement. *(b)* Computer generated hologram for OV with $l = 1$. The MDL *(c)* microscope image, and *(d)* phase distribution. *(e)* The propagation of input OV with $l = 1$ through the MDL, showing formation of optical vortex needle beam. Note, d denotes the focusing distance of MDL, and z denotes the propagation distance of FOV. *(f)* Intensity profile of FOZ at z = 2 cm. *(g)* Interference between FOV and Gaussian beam, confirming the value of $l = 1$ of FOV. DOF: Depth of focus; SLM: Spatial light modulator; L_1, L_2, L_3, and L_4: Plano-convex lenses with focal length f_1, f_2, f_3, and f_4, respectively; CA: Aperture.

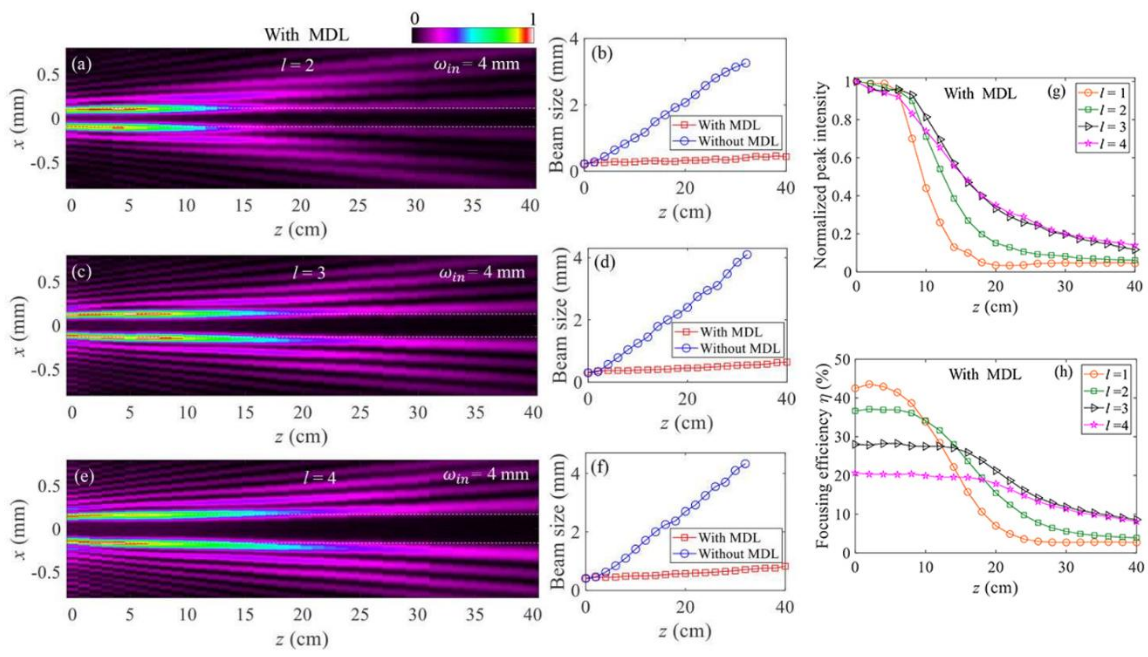

Figure 2: Experimental results of FOV with different l values, when MDL is illuminated with an input optical vortex of size ω_{in} = 4 mm. Evolution of intensity of FOV in the x-z plane and measured beam size with z for FOV (with MDL) and OV (without MDL) for *(a)* and *(b)* $l = 2$, *(c)* and *(d)* $l = 3$, and *(e)* and *(f)* $l = 4$. For different values of l, the FOV's *(g)* normalized peak intensity, and *(h)* focusing efficiency, as a function of z.